5. PARAMETRIC STUDY

5.1 INTRODUCTION

Before applying 'model F', it is important to determine how sensitive it is to variations in numerical and input parameters. In this chapter, parameters of interest are varied through reasonable ranges in order to establish their importance or non-importance on the crack initiation life N_{CI} and on the total fatigue life of the detail N_f. All of the results obtained from parametric study are *normalized* with respect to the crack initiation life, N_{CI0} and the total fatigue life, N_{f0}. The values of N_{CI0} and N_{f0} are obtained from the crack propagation simulation with the 'reference case'. Three tasks of this chapter are : 1) to determine the sensitivity of crack propagation simulation results on the variation of modeling parameters ; 2) to classify modeling parameters as functions of their importance on the modeling results ; and 3) to establish application limits of the model.

The parameters studied, are classified into 4 groups :

1. *numerical* parameters :
   - element size, δ;
   - the amount of elements used at the same time, n_{local} ;
   - use of Glinka's ESED criterion or Neuber's rule ;
   - crack tip radius, ρ.
2. *material* parameters :
   - elastic modulus E and cyclic yield stress σ'_{ys}, ;
   - constants of Ramberg-Osgood Equations (3.19) and (3.17) ;
   - constants of strain-life relationship (3.11) ;
   - the influence of the *steel type*.
3. *geometry* parameters :
   - plastic constraint factor, *pcf* (the influence of the plate thickness) ;
   - distribution of fabrication induced residual stresses, $\sigma_{res}(x)$;
   - distribution of the stress concentration factor, $SCF(x)$.
4. *load* parameters :
   - constant-amplitude stress range, $\Delta\sigma_0$;
   - ratio of minimum and maximum nominal stress, R ;
   - variable-amplitude load history.

5.2 REFERENCE CASE

The *numerical* parameters of the 'reference case' are given in Table 5.1.

δ [mm]	n_{local}	ρ [mm]	Glinka's ESED criterion or Neuber's rule
0.1	5	0.01	ESED criterion

Table 5.1 : *Numerical parameters of the 'reference case'.*

The material of the 'reference case' is steel type *St 50*. The *material* parameters of the steel *St 50* are taken from the [5.1] and presented in Table 5.2.

Elastic modulus and cyclic yield stress		Constants of Ramberg-Osgood Equations	
σ'_{ys} [N/mm^2]	E [N/mm^2]	n'	K' [N/mm^2]
329	210000	0.172	957
Constants of strain-life relationship			
σ_f' [N/mm^2]	b'	ε_f'	c'
829	-0.098	0.415	-0.565

Table 5.2 : *Material parameters of the 'reference case'.*

The *detail geometry* and *loading* used, are presented in Figure 5.1. The loading assumed in the 'reference case' was chosen in a way such that the number of cycles corresponding to the final crack length, a_{cr}, were approximately:

$$N_{f0} \approx 10^6 \text{ [load cycles]} \tag{5.1}$$

and the crack initiation life, N_{CI0} :

$$N_{CI0} \approx 0.5 \cdot N_{f0} \approx 5 \cdot 10^5 \text{ [load cycles]} \tag{5.2}$$

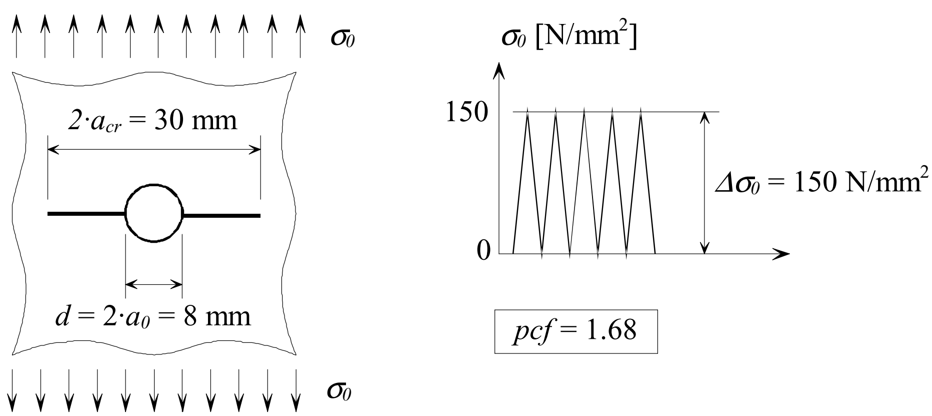

Figure 5.1 : *Detail geometry and loading of the 'reference case'.*

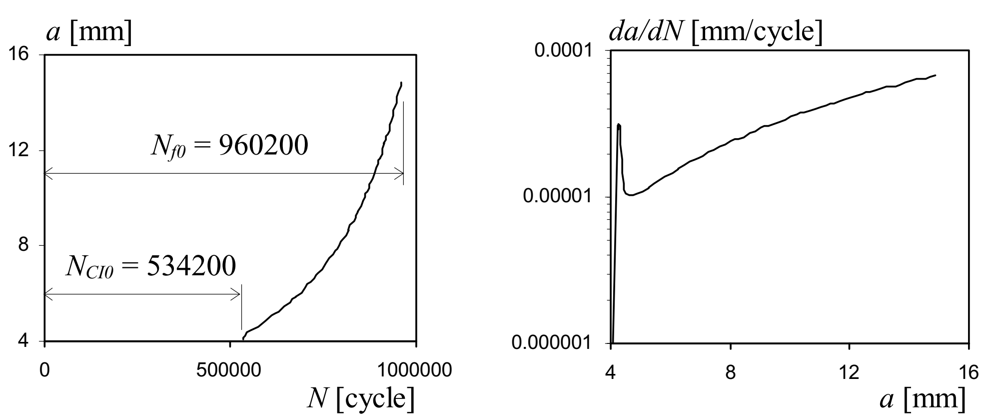

Figure 5.2 : *Crack propagation simulation results of the 'reference case'.*

The results of the crack propagation simulation for the '*reference case*' are presented in Figure 5.2. The results of the *parametric study* are presented as functions of their influence on fatigue behavior. If the results satisfy conditions (5.3) or (5.4), then they are presented on a *linear* scale. If the results do *not* satisfy the conditions (5.3) or (5.4), then they are presented on a *logarithmic* scale.

$$\frac{N_{CI}}{N_{CI\,0}} \in \left[0.5 \ldots 2\right] \tag{5.3}$$

$$\frac{N_f}{N_{f\,0}} \in \left[0.5 \ldots 2\right] \tag{5.4}$$

5.3 NUMERICAL PARAMETERS

The values of the numerical parameters depend on the assumptions and modeling principles established in Section 3.1. The limits of the numerical parameters are fixed. The values of the numerical parameters should be chosen so that computing time is minimized and the accuracy of the results is not influenced.

5.3.1 Element Size

The limits of the element size are fixed by condition (5.5) (see Clause 3.2.3). Simulations were carried out varying δ within the range given by the same condition.

$$\delta \in [0.05 \ldots 0.15] \ \text{[mm]} \tag{5.5}$$

The results are presented in Figure 5.3, and indicated the following:
– the influence of δ on the values of N_{CI} and N_f is less than ±25%.
– The total fatigue life is influenced more by the variation of δ, than the crack initiation life. This is because N_{CI} is only influenced by the variation in size of the first element, while N_f is influenced by variation of the size of all elements.

It can be concluded, that the element size δ, if varied within the limits given by condition (5.5), has no significant influence on crack propagation simulation results.

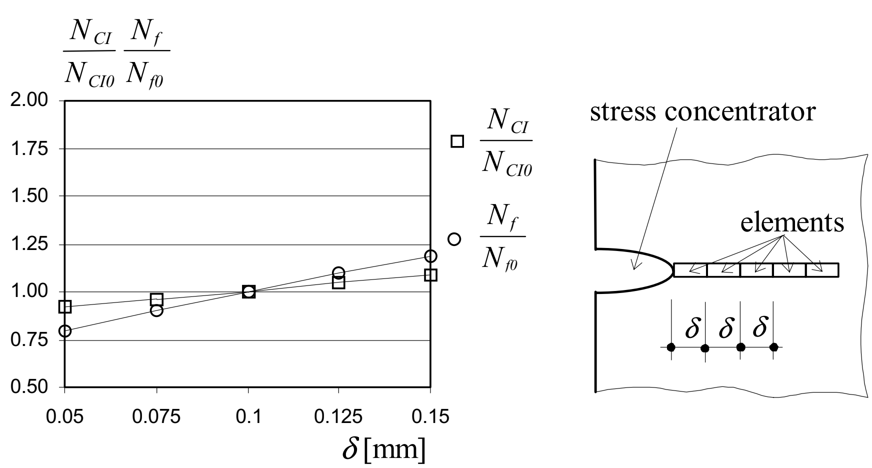

***Figure 5.3 :** The influence of the element size.*

5.3.2 Amount of Elements

The amount or number of elements used in the calculations can vary within the limits :

$$n_{local} \in [1 \ldots n_{global}] \tag{5.6}$$

A choice of $n_{local} = n_{global}$ would avoid the extrapolation of the initial damage of added elements (see Clause 3.4.4). On the other hand, if the value of n_{local} is high, the computing time increases. Therefore, in order to reduce computing time, the n_{local} should be made as small as possible. Crack propagation simulations were carried out, varying n_{local} from 4 to 8. The results are presented in Figure 5.4 and indicate the following :

- the number of elements used in the calculations, has almost no influence on N_{CI}.
- If the minimum amount of elements ($n_{local} = 4$) is used, then total fatigue life is slightly shorter than for other values of n_{local}. The effect varying the number of elements becomes insignificant if $n_{local} \geq 5$.

It can be concluded that a variation in the number of elements used at the same time in the calculations has no effect on the results obtained from the crack propagation simulation. In order to keep computing time at a minimum, $n_{local}=5$ is recommended.

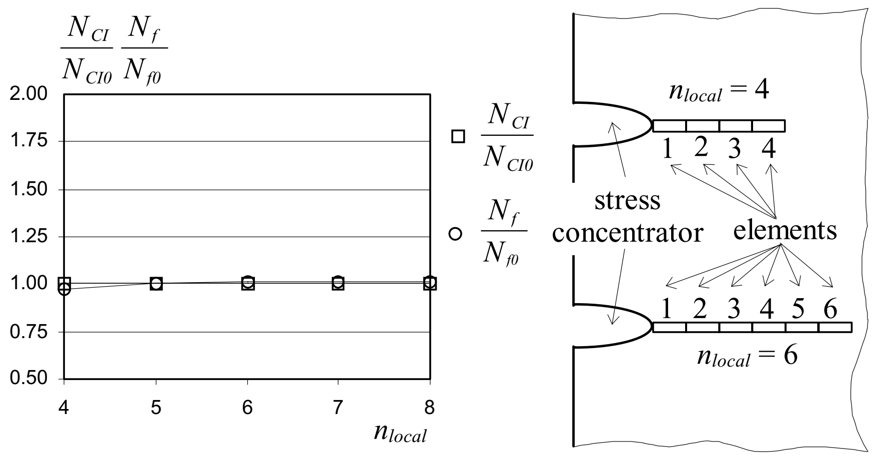

Figure 5.4 : *The influence of* n_{local}.

5.3.3 Crack Tip Radius

There are two methods that can be used to calculate the loading of elements at the crack tip. The methods are given by Equation (3.18) or Equation (A.3). The former equation corresponds to sharp crack while the latter to a *blunted* crack with a tip radius ρ. The crack tip radius can be assumed to be equal to the material grain size [5.2]. The assumed crack tip radius for the 'reference case' is taken as 0.01 mm which corresponds to the average material grain size in most steels.

In the simulations, the radius of the crack tip was varied within a range of $\rho=0.005...0.05$. The results are presented in Figure 5.5. From Figure 5.5, the following observations can be made :

- the crack tip radius ρ (as would be expected) has no effect on the crack initiation life.
- The crack tip radius has a small effect on the total fatigue life. Using Equation (3.18) ($\rho=0$) always leads to more conservative crack propagation results than the corresponding equation for a blunted crack.

It can be concluded that the crack tip radius has a small effect on simulation results Equation (3.18) is sufficient for use in 'model F'.

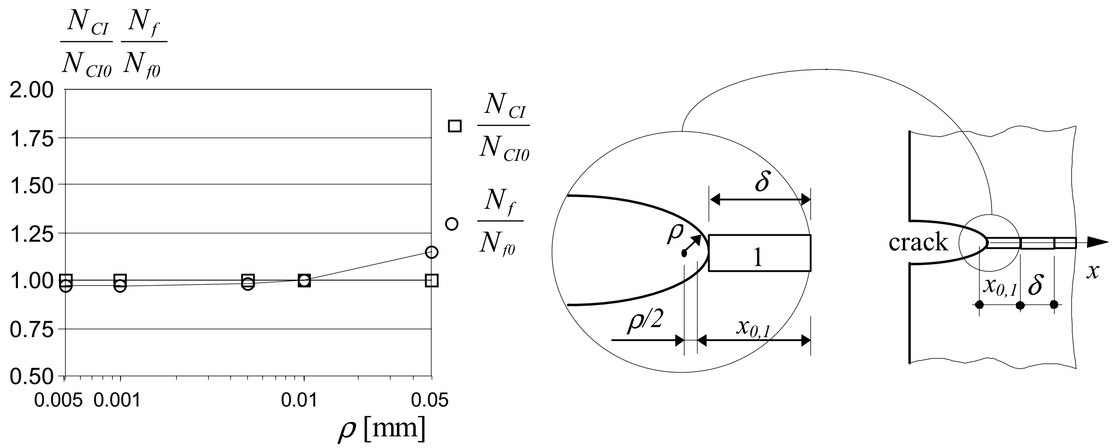

***Figure 5.5 :** The influence of the crack tip radius.*

5.3.4 Neuber's rule versus Glinka's ESED criterion

There are two methods available to calculate the elastic-plastic load response of elements under linear elastic loading. The methods are known as Glinka's ESED criterion and Neuber's rule, respectively. In 'model F', Glinka's ESED criterion is used because Neuber's rule results in overly conservative results [5.3], [5.4]. A comparison of the influence of Neuber's rule to the influence of Glinka's ESED criterion is presented in Figure 5.6. It can be clearly seen that use of Neuber's rule leads to about 30...35% shorter crack initiation life and a total fatigue life than obtained using Glinka's ESED criterion.

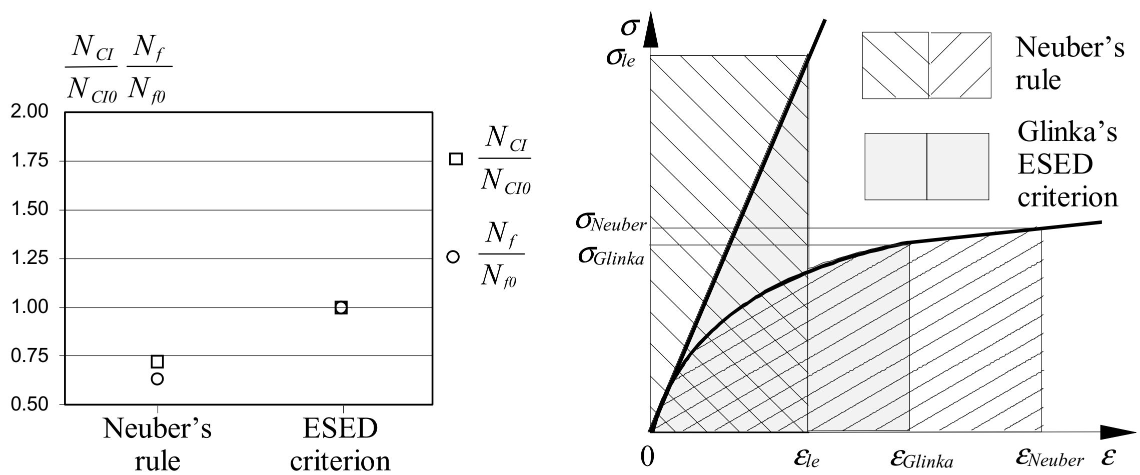

***Figure 5.6 :** The influence of Neuber rule versus Glinka's ESED criterion.*

5.4 MATERIAL PARAMETERS

There are eight material parameters introduced into 'model F'. It is difficult to determine the exact upper and lower limits of each of the eight material parameters within the steel type. Therefore, the crack propagation simulations were conducted with an estimated variation range of material parameters.

5.4.1 Elastic Modulus and Cyclic Yield Stress

Elastic Modulus

The elastic modulus E is used in all material behavior laws utilized in the modeling. The relationship of the material linear-elastic stress-strain behavior, the Ramberg-Osgood Equations (3.19) and (3.20), and the strain-life relationship (3.11) all are influenced by E. In addition, E is introduced in the crack closure model in order to calculate the crack opening displacement *CTOD*. For the parametric study, the elastic modulus is varied within the following limits :

$$E \in [190'000...230'000] \ \ [\mathrm{N/mm^2}] \tag{5.7}$$

The results of the simulation in Figure 5.7a indicate that the effect of E on the crack initiation stage and the total fatigue life is less than ±10% if varied within the range given by condition (5.7).

Cyclic yield stress

Cyclic yield stress is only introduced into the crack closure model (Section 3.5). For the simulations, the cyclic yield stress was varied within the range typical for structural steels :

$$\sigma'_{ys} \in (250...450) \ \ [\mathrm{N/mm^2}] \tag{5.8}$$

The results of the simulation presented in Figure 5.7b show that the variation of the yield stress does not influence the crack initiation stage nor the total fatigue life.

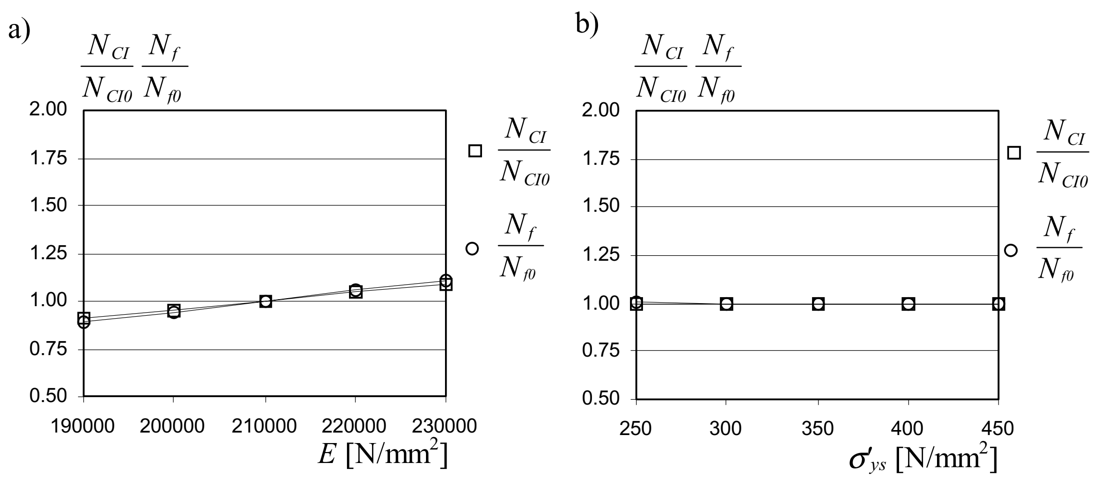

Figure 5.7 : *The influence of the elastic modulus (a) and the cyclic yield stress (b).*

It can be concluded that neither the elastic modulus nor the yield stress have a significant effect on crack initiation and total fatigue life. However, E appears to have more of an influence on the fatigue behavior than σ'_{ys}.

5.4.2 Constants of the Ramberg-Osgood Equations

The Ramberg-Osgood Equations (3.19) and (3.20) were chosen to model the cyclic non-linear stress-strain behavior of the material. In this section, the influence of the cyclic strain hardening exponent n', and the cyclic strength coefficient K', is shown.

Cyclic Strain Hardening Exponent

The cyclic strain hardening exponent *n'* , is varied within the range common to structural steels :

$$n' \in [0.1...0.2] \tag{5.9}$$

The results of the simulation shown in Figure 5.8a indicate that the variation of *n'* has an influences the total fatigue life (N_f) by less than 15%. On the other hand, the variation of *n'* has an influence of about 10...30% on the crack initiation life N_{CI}. It is interesting to note that a low strain hardening exponent results in a much faster crack initiation than a higher strain hardening exponent. This can be explained by the fact that a lower *n'* leads to larger strain ranges and consequently, to shorter fatigue life of the elements. Figure 5.8a also shows that an optimum value for *n'*, from the fatigue life point of view exists : taking *n'=0.15* always leads to a longer fatigue life than other values of *n'*.

Cyclic Strength Coefficient

The cyclic strength coefficient *K'* is varied within the range common for structural steels :

$$K' \in [800...1200] \text{ [N/mm}^2\text{]} \tag{5.10}$$

Simulation results in Figure 5.8b show that the variation of *K'* has a small effect on both the crack initiation life and the total fatigue life. It can also be seen that the variation of *K'* has a greater effect on N_{CI} than on N_f.

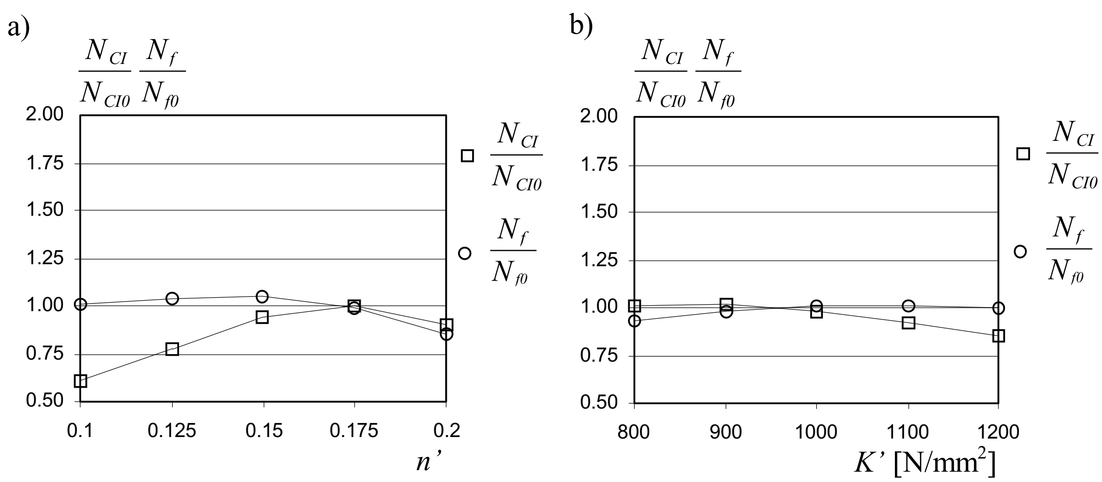

Figure 5.8 : *The influence of the cyclic strain hardening exponent (a) and the cyclic strength coefficient (b).*

It can be concluded, that the constants used in the Ramberg-Osgood equations have little effect on the crack initiation life and the total fatigue life. The parametric study indicates the optimum values for *n'* and *K'*.

5.4.3 Constants of Strain-Life Relationship

In this section, the influence of the variation of the four constants in the strain-life relationship (3.11) is studied. In order to have an idea about the variation range of the strain-life relationship constants, 24 sets of these constants for the unalloyed steels St 52, St 50, St 46, St 42 and St 37, were chosen from [5.1], and statistically analyzed. The values of the constants, mean values and standard deviations are given at the center in Figures 5.9, 5.10, 5.11 and 5.12. The range of variation of the constants used in the parametric study is also indicated at the center in the same figures using arrows.

Fatigue Strength Coefficient and Exponent

The fatigue strength coefficient σ_f' was varied within range 700...1100 N/mm^2. The results presented in Figure 5.9 show that both the crack initiation life and the total fatigue life are very sensitive to the variation of σ_f'. Results show that the crack initiation life, N_{CI}, is more sensitive to the variation of σ_f' than the total fatigue life N_f. This is because the variation of σ_f' influences the strain-life relationship in the region where the strain range $\Delta\varepsilon$ is small (see Figure 5.9, right). Since the strain range of the elements at the *crack initiators* are small, compared to the strain ranges of the elements at *fatigue crack*, the crack initiation life is influenced more by the variation of σ_f' than the total fatigue life. It can therefore be concluded that the fatigue strength coefficient is an important material parameter that has a great influence on crack initiation and the total fatigue life.

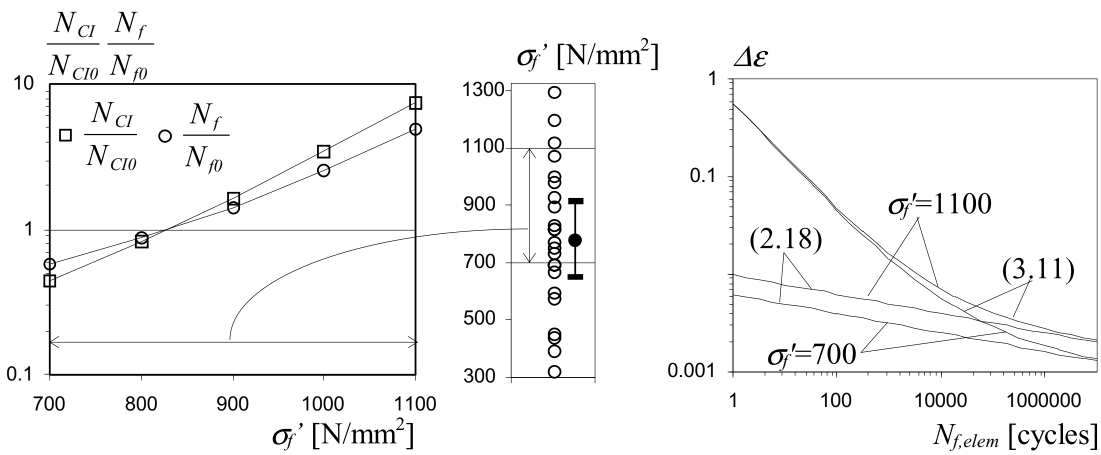

***Figure 5.9 :** The influence of the fatigue strength coefficient.*

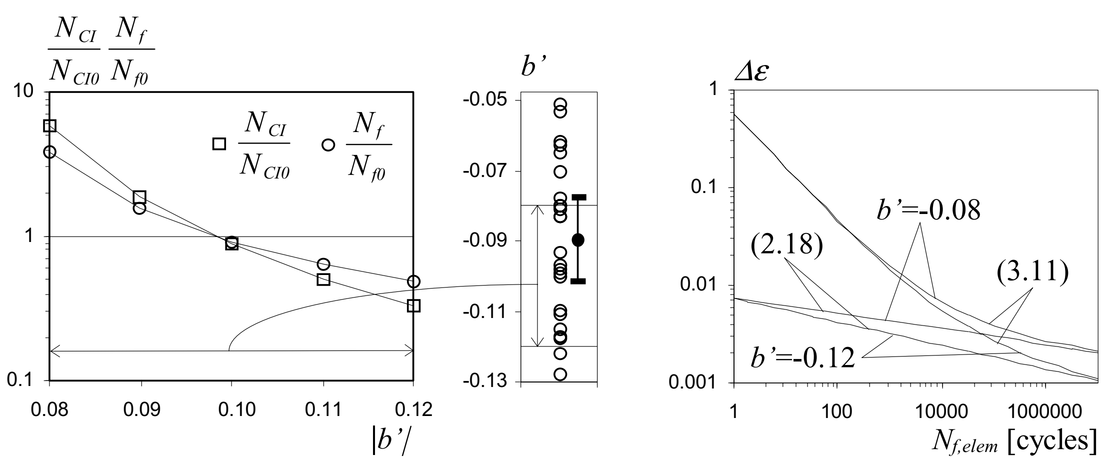

***Figure 5.10 :** The influence of the fatigue strength exponent.*

The fatigue strength exponent b' was varied within the range 0.08...0.12. The results presented in Figure 5.10 show that both the crack initiation life and the total fatigue life are very sensitive to the variation of *b'*. However, the crack initiation life N_{CI} is more sensitive to the variation of *b'* than the total fatigue life N_f. This could be because the variation of *b'* influences the strain-life relationship in the region where the strain range $\Delta\varepsilon$ is small (see Figure 5.10, right). Since the strain range of the elements at the *crack initiators* are small compared to the strain ranges of the elements at *fatigue crack*, the crack initiation life is more influenced by variation of *b'* than the total fatigue life. It can therefore be concluded that the fatigue strength exponent is an important material parameter which has a great influence on crack initiation and the total fatigue life.

Fatigue Ductility Coefficient and Exponent

The fatigue ductility coefficient ε_f' was varied within the range 0.2...0.6. The results presented in Figure 5.11 indicate that both the crack initiation life and the total fatigue life are very sensitive to the variation of ε_f'.

The fatigue ductility exponent *c'* was varied within the range -0.65...-0.45 The results presented in Figure 5.12 show that both the crack initiation life and the total fatigue life are very sensitive to the variation of *c'*.

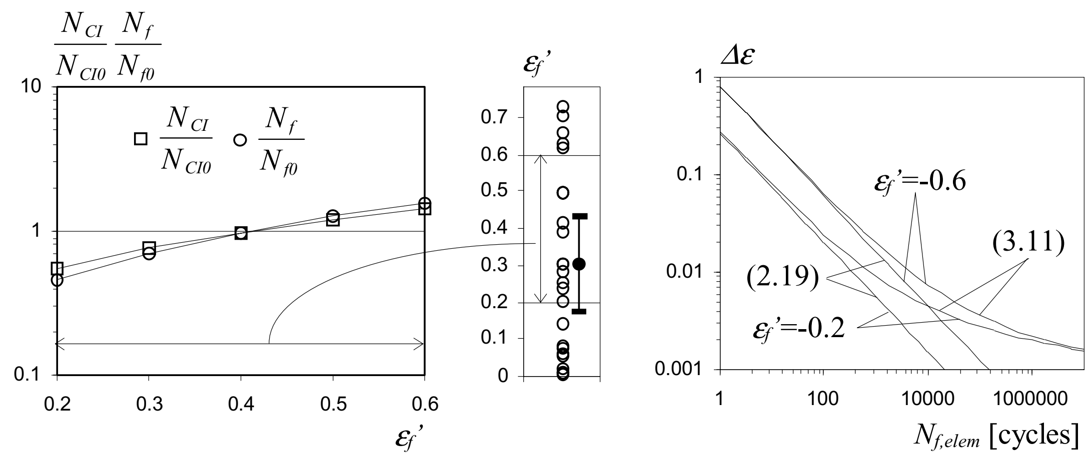

Figure 5.11 : *The influence of the fatigue ductility coefficient.*

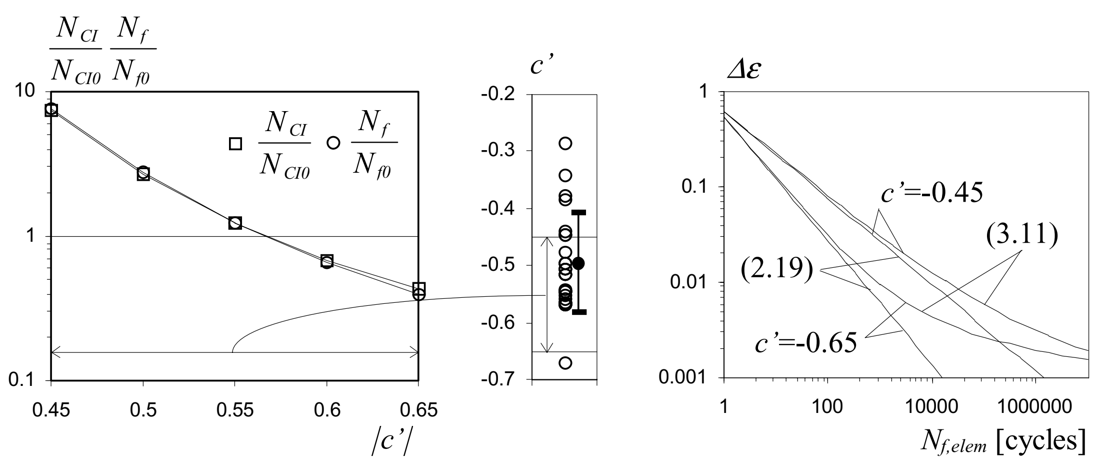

Figure 5.12 : *The influence of the fatigue ductility exponent.*

In summary, it can be seen that the variation of all four constants of the strain-life relationship have a large influence on the results obtained from a crack propagation simulation. It is important to determine values for these constants with the best possible accuracy.

5.4.4 Steel Type

All of the material parameters studied change with a change in the steel type[1]. In this section, it is shown how the variation of the steel type influences the results of the crack propagation simulation. Simulations were carried out on five frequently used structural steels : St37, St42, St46, St50 and St52. The material parameters for these steels were taken from [5.1]. Each of the five compared steel grades contains several steel types. Each type of steel is presented in Figure 5.13 as a data point. Data from the same steel grade are connected with a line in the figure.

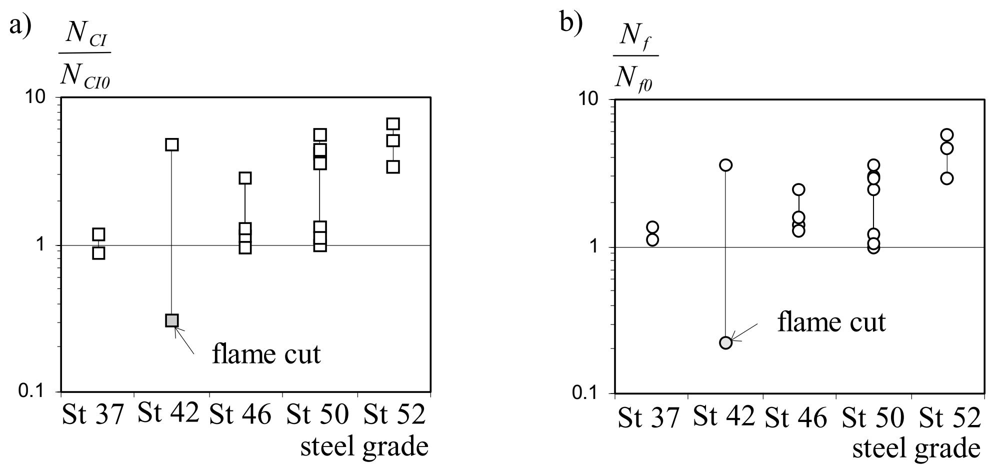

Figure 5.13 : *The influence of the steel grade (and steel type).*

The results indicate that :

- both the crack initiation life and the total fatigue life are quite sensitive to a variation of the steel type.
- One data point labeled 'flame cut' falls significantly below the other data. The 'weakness' of this steel type results from an extremely low value of the fatigue ductility coefficient : $\varepsilon_f' = 0.0629$. This is because the material of the smooth test specimens used to determine this set of material parameters was flame cut.
- The test conditions and the quality of the rough material of the smooth test specimen have a great influence on the values of the strain-life relationship constants and therefore on the results of the simulation.
- The St52 and St42 steels (except those that were 'flame cut') are better steels from a fatigue point of view than the St50, St46 and St37 steels.
- There appears is to be a contradiction between the results in Figure 5.7 and Figure 5.13. Since the steels are graded according to the yield stress, a study of the influence of the yield stress *should* lead to the same results as the results of the steel type. It must be said,

[1] Here 'steel type' means a *set* of material (cyclic) parameters, including the constants of strain-life relationship as well as the constants of Ramberg-Osgood equation and cyclic yield stress. Material parameters are determined by constant-amplitude fatigue testing of smooth specimens. Material parameters of each steel type depend on microstructure of the steel, on the treatment of rough material (=treatment of semi-finished material - cold rolling or flame cut, for example), but also on the test conditions (test temperature and loading frequency, for example).

however, that the influence of steel type on the results is largely due to the influence of material parameters other than yield stress. For example, the influence of yield stress on fatigue behavior is considerably less than the influence of the constants of strain-life relationship.

It can be concluded that the type of steel has a significant influence on the crack initiation life and on the total fatigue life. Designers must pay more attention to the choice of the steel. Selection of the appropriate design material may lead to a significant gain in fatigue resistance of the detail.

5.5 GEOMETRY PARAMETERS

In the following section, the influence of several parameters related to detail geometry on fatigue behavior is investigated. The analysis includes three geometry-related parameters; 1) plastic constraint factor, 2) distribution of fabrication-introduced residual stresses, and 3) distribution of the stress concentration factor.

5.5.1 Plastic Constraint Factor

The plastic constraint factor was varied within from 1...3. A value of *pcf = 1* corresponds to a plain stress state on the plate surface and/or in a *thin* plate. A *pcf = 3* corresponds to a plain strain state inside a *thick* plate.

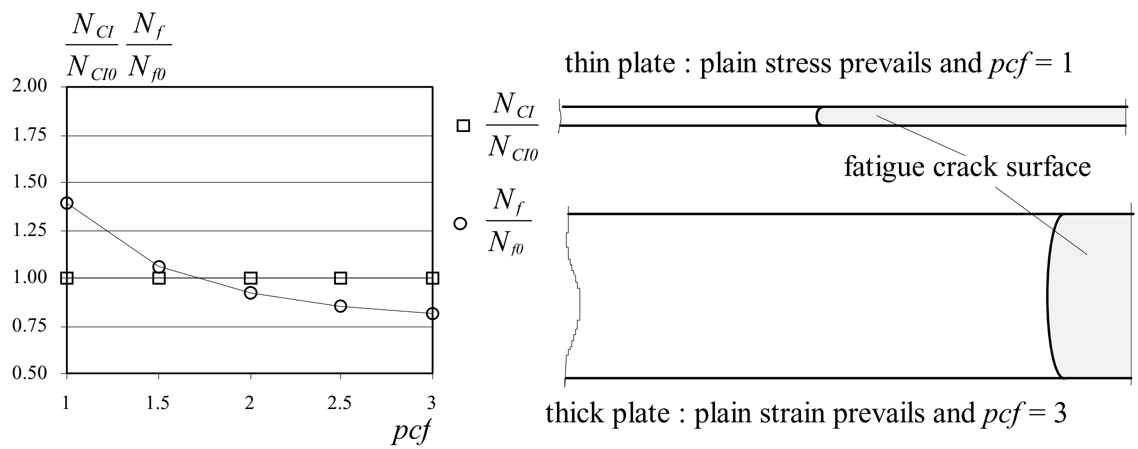

Figure 5.14 : *The influence of the plastic constraint factor.*

The results of the parametric study are presented in Figure 5.14 and indicate the following :

– the plastic constraint factor has no effect on the crack initiation. This is expected because the crack initiation generally takes place near the plate surface where plain stress dominates.
– Cracks in a *thin* plate have longer fatigue lives than equivalent cracks a in *thick* plate.
– The fatigue life for a *thin* 'reference case' plate, is about 1.7 times longer than the fatigue life for a *thick* 'reference case' plate.

It can be concluded that plate thickness, represented by the plastic constraint factor, has a moderate effect on the total fatigue life.

5.5.2 Residual Stress Distribution

In order to show the influence of residual stresses on fatigue crack behavior, five distinct residual stress distributions are compared, four of which are presented in Figure 5.15. Case 3 -

the ‘reference case’, is assumed to have no residual stresses. The absolute values of the maximum and minimum residual stress in the distribution were taken equal to the maximum nominal stress. The results of the study are presented in Figure 5.15.

The results show that :
- both the crack initiation life and the total fatigue life are influenced by the residual stress distribution.
- The influence of residual stress distribution on crack initiation depends on the magnitude of the residual stress near the stress concentrator. As a result, the crack initiation life for case 1 is almost equal to the crack initiation life for case 2 and the crack initiation life for case 4 is almost equal to the crack initiation life for case 5.
- The influence of the residual stress distribution on fatigue crack propagation is more important at for small crack lengths ($x<a_{cr}/3$). If a crack is longer than $a_{cr}/3$, then the influences of residual stresses decreases significantly. As a result, cases 4 and 5 posses similar fatigue lives even though the distribution of residual stresses at the region $x>a_{cr}/2$ are different.
- The compressive residual stresses applied in the region where x is small (cases 1 and 2), can lead to a large increase in the fatigue life of the detail. This phenomenon is well studied and some weld improvement methods are based on this phenomenon [5.5], [5.6]. On the other hand, the relatively high tensile residual stresses applied in the region where x is small (cases 4 and 5), do not lead to a significantly shorter fatigue life than if the detail possesed no residual stress (case 3).

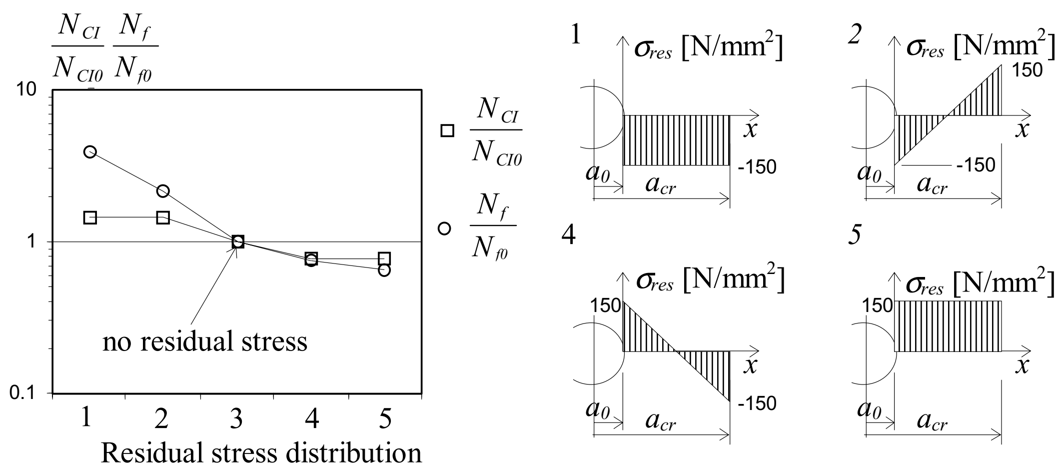

Figure 5.15 : *The influence of the residual stress distribution.*

It can be concluded, that fabrication-introduced residual stress in a detail is an important parameter that must be taken into account during crack propagation modeling. Their influence is mainly a function of the residual stress distribution in the region that is close to the stress concentrator. However, fabrication-introduced residual stresses that are some distance away from a stress concentrator do not have a significant influence on the fatigue life.

5.5.3 Stress Concentration Factor Distribution

The geometry of the detail can be normalized using the stress concentration factor distribution (see Section 2.2). This implies that the effects of detail geometry on fatigue behavior can be studied using the stress concentration factor *distribution* instead. In this section, the effects of *seven* distributions of stress concentration factor on fatigue crack initiation life and total fatigue life is studied.

The stress concentration factor distributions used in the study, *SCF(x)*, are drawn using bi-linear curves, where each bi-linear curve is defined by three points (Figure 5.16 up). The coordinates of the *first* point are determined by conditions (5.11) and (5.12) :

$$x_1 = a_0 \tag{5.11}$$

$$SCF(x_1) = SCF_{max} \in [2.25 \ldots 7] \tag{5.12}$$

The coordinates of the *second* point are determined by conditions (5.13) and (5.14) :

$$x_2 = a_{cr} \tag{5.13}$$

$$SCF(x_2) = 1 \tag{5.14}$$

The coordinates of the *third* point, at the intersection point of the two bi-linear curves, are determined by conditions (5.15) and (5.16). The x-coordinate of the *third* point, x_3, is chosen so that the area below the bi-linear stress concentration factor distribution is equal to the area below the stress concentration factor distribution for the 'reference case'.

$$\int_{a_0}^{a_{cr}} SCF_{bi-linear}(x_3)dx = \int_{a_0}^{a_{cr}} SCF_{'reference-case'}(x_3)dx \tag{5.15}$$

$$SCF(x_3) = 1 \tag{5.16}$$

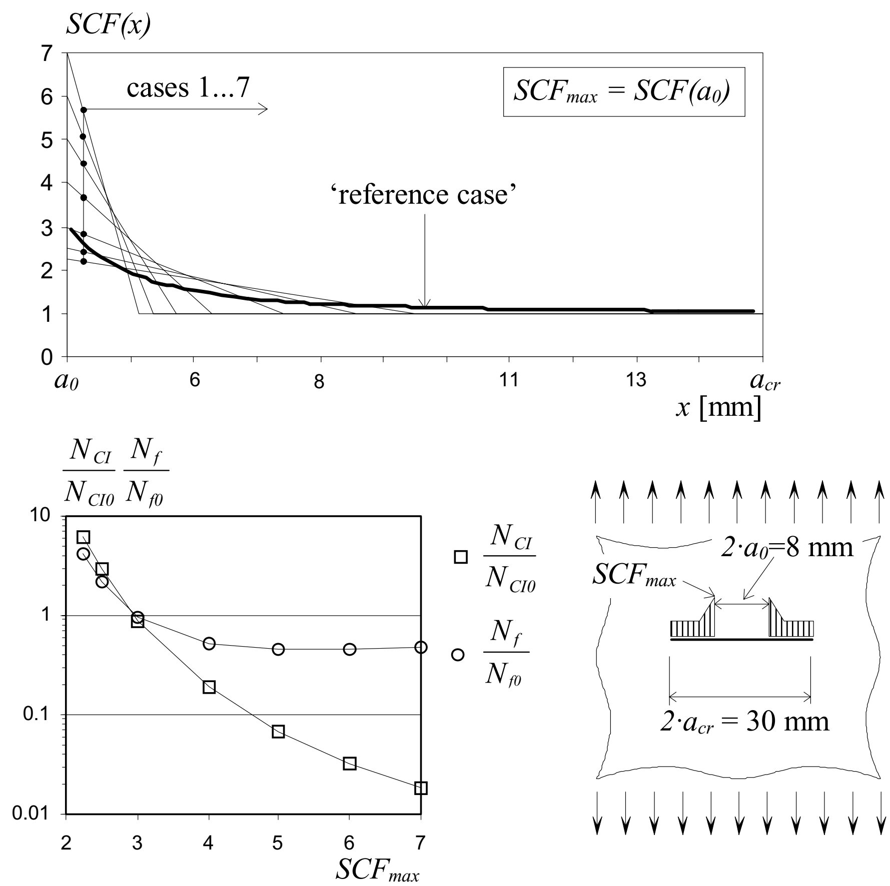

Figure 5.16 : *The influence of the stress concentration factor distribution.*

It can be seen that the stress concentration factor distributions with high SCF_{max} are characteristic to welded details. On the other hand, the stress concentration factor distributions with low SCF_{max} are characteristic to details containing holes and notches. The results of the study are presented in Figure 5.16, below.

The results indicate that :
– the crack initiation life N_{CI} is heavily influenced by the maximum value of the stress concentration factor SCF_{max}.
– A gain in the total fatigue life N_f is obtained as a result of the long crack initiation life. The crack initiation life is a function of the maximum stress concentration factor SCF_{max}. When the values of SCF_{max} are large, the total fatigue life will essentially remain a constant value. This behavior results from a very short crack initiation and an almost constant stable crack growth period[1].

It can be concluded that the distribution of the stress concentration factor is a very important fatigue parameter since it has a great effect on the crack initiation life and the total fatigue life. Thus, improving this parameter by reducing weld toe angle and radius, for example, is very effective.

5.6 LOAD PARAMETERS

In this section the influences of several load related parameters on fatigue behavior are investigated. The influences of three load parameters are studied. These are : 1)constant-amplitude nominal stress range $\Delta\sigma_0$, 2) ratio of the minimum and maximum nominal stress R, and 3) variable-amplitude load histories.

5.6.1 Nominal Stress Range

The constant-amplitude nominal stress range $\Delta\sigma_0$ was varied between 70...450 N/mm^2. The nominal stress ratio is taken $R=0$. The results of the study and the fatigue resistance curve for detail category 90 are presented in Figure 5.17. Detail category 90 corresponds to a plate with a hole in the center [5.7].

The results indicate that :
– the constant-amplitude nominal load range $\Delta\sigma_0$ has a greatly affects the crack initiation life and the total fatigue life.
– When values of $\Delta\sigma_0$ are high, the simulated curve for the total fatigue life matches relatively well with the DC90 curve. However, when values of $\Delta\sigma_0$ are less, the simulated curve predicts a much higher fatigue threshold than the *S-N* curve from [5.7]. Because the DC90 curve contains safety factors, its fatigue threshold is reduced resulting in the difference between the simulated curve and the DC90 curve.
– For the detail used, the crack initiation life is considerably longer than the stable crack growth period. This results in a total fatigue life approximately equal the crack initiation life. However, for a different detail geometry this may not be the case.

It can be concluded, that the nominal load range is a very important fatigue parameter, a confirmation of a well known fact. The reason why it is presented here, is to show that ‘model F’ can reasonably simulate the *S-N* curves.

[1] Some weld improvement methods are based on change of weld toe geometry in order to decrease the stress concentration factor at the weld toe. Based on the results of the parametric study it can be said that the greatest weld improvement effect can be obtained if the maximum stress concentration factor near the weld toe is reduced to the values smaller than ~3.5 (this may be obtained using TIG welding, for example).

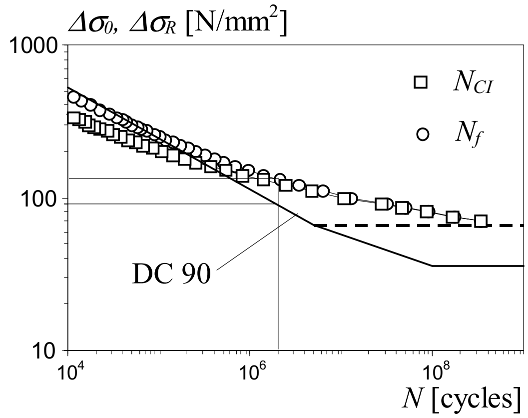

***Figure 5.17 :** The influence of the nominal stress range.*

5.6.2 Ratio of the Minimum and Maximum Nominal Stress

Simulations of the fatigue crack propagation are carried out by varying the ratio of minimum and maximum nominal stress R, within the range of -1...0.5. The calculations are carried out for four different levels of $\Delta\sigma_0$ ($\Delta\sigma_0$ =100, 150, 200 and 250 N/mm^2. The results of the simulation are presented in Figure 5.18. The results show that :

– the ratio of the minimum and maximum nominal stress R, has a very large effect on the crack initiation life N_{CI}, as well as on the total fatigue life N_f.
– The influence of R on the crack initiation life N_{CI} increases if $\Delta\sigma_0$ decreases. This is due to fact that at low $\Delta\sigma_0$, the elastic part of the strain-life relationship dominates. The elastic-plastic mean stress σ_m, in elastic part of the strain-life relationship, depends on the ratio R.
– The influence of R on the total fatigue life N_f is greater within the region of $R<0$. This is a result of the crack closure effect (i.e., a decrease in R results in decrease in the effective nominal stress range $\Delta\sigma_{0,eff}$, and a corresponding increase in the total fatigue life N_f).

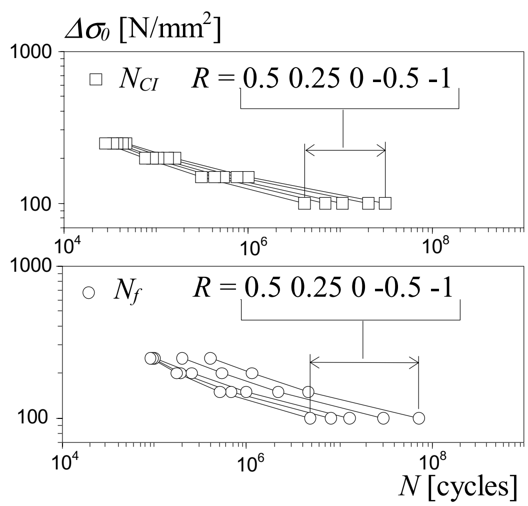

***Figure 5.18 :** The influence of the ratio of the minimum and maximum nominal stress R.*

The curves in Figure 5.18 can be used to determine the approximate *effective* nominal stress range $\Delta\sigma_{0,eff}$. A calculation procedure for $\Delta\sigma_{0,eff}$ is explained in Annex A.4.1. It can be concluded that the ratio of the minimum and maximum nominal stress R is an important parameter which must be taken into account for fatigue calculations.

5.6.3 Variable-Amplitude Load History

The purpose of this section is to illustrate the difference between simulations of crack propagation made using variable-amplitude load histories and equivalent constant-amplitude load range. The variable-amplitude load histories used are varied such that the equivalent constant-amplitude load range varies within range: 70...220 N/mm^2. The equivalent constant-amplitude stress range $\Delta\sigma_e$, is calculated using Equation (5.17), the simplest method available to calculate $\Delta\sigma_e$. Because Equation (5.17) has a simple form, it is quite often used. There other formulae exist for the equivalent constant-amplitude stress range [5.8].

$$\Delta\sigma_e = \left(\frac{\sum_i n_i \cdot \Delta\sigma_{0,i}^{\ 3}}{\sum_i n_i} \right)^{\frac{1}{3}} \tag{5.17}$$

The stress range $\Delta\sigma_{0,i}$, in Equation (5.17), is calculated using the rainflow counting method. The shape of the load histories studied remained unchanged. The normalized shape of load histories is presented in the right half of Figure 5.19. The results of the simulation are presented in the left half of Figure 5.19. The results show that :

– simulations with variable-amplitude load histories *always* lead to smaller values of N_{CI} and N_f than simulations using an equivalent constant-amplitude load range.
– *Non-conservatism* of the equivalent constant-amplitude load range compared to the variable-amplitude load histories increases as $\Delta\sigma_e$ decreases.

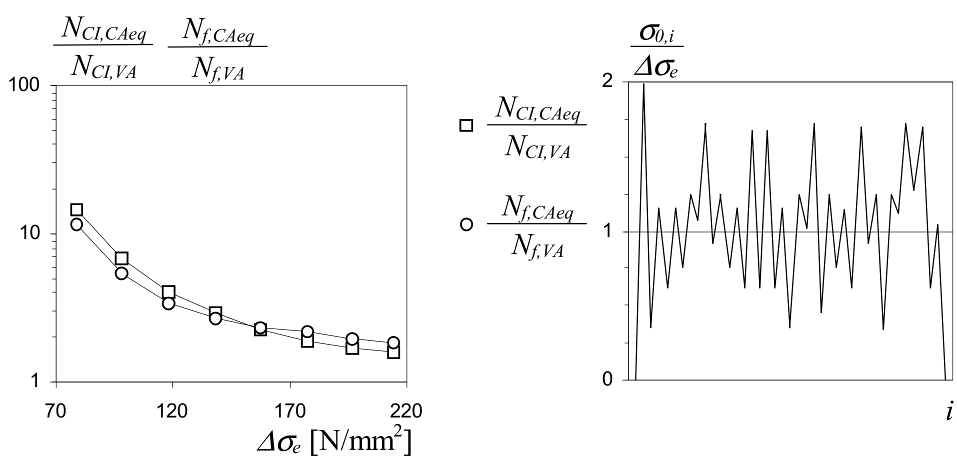

Figure 5.19 : *The influence of variable-amplitude load history.*

Unfortunately, it is impossible, to make any general conclusions. The two remarks made above, are only valid for the load histories, detail geometry and material properties investigated. A brief analysis of the variable-amplitude fatigue behavior is presented also in Clause 6.4.2.

5.7 DISCUSSION OF THE MODEL

New fatigue crack propagation model was created in Chapter 3, verified in Chapter 4, and analyzed using parametric study in this chapter. This section establishes the application limits and application field, and outlines the advantages and disadvantages of created model - ‘model F’.

5.7.1 Application Limits

Limits of application are divided into two groups : 1) limits due to theoretical assumptions, and 2) limits due to input data.

Limits due to Theoretical Assumptions

There are four application limits of 'model F' related to theoretical assumptions of the model :
- only *mode I* crack propagation can be analyzed.
- The amount of local elements used at the same time in calculations n_{local}, is limited to:

$$4 \le n_{local} \le n_{global} \tag{5.18}$$

- The limits on element size δ are established by condition (5.19). If 'model F' is applied on the analysis of details made of aluminum, the limits of the element size should be reviewed. This is due to fact that micro-structure of aluminum differs of that of steel.

$$0.05 \le \delta \le 0.15 \text{ [mm]} \tag{5.19}$$

- The requirement that small scale yielding must be satisfied according to linear-elastic fracture mechanics. Thus, the crack tip plastic zone size must be less than ~30% of the resistant area of the net section :

$$r_{pl} \le \sim 0.3 \cdot (W-a) \tag{5.20}$$

Limits on Input Data

The 'model F' has four groups of input data : 1) material properties, 2) detail geometry, 3) loading history, and 4) residual stresses. The application limits of 'model F' on these groups of data are given below.

Materials. 'Model F' is verified on structural steels only. Although aluminum was included into the scope of modeling, no comparisons of the model were carried out to the test data of aluminum. 'Model F' is based on strain-life relationship (3.11). Since fatigue behavior of aluminum can also be characterized by strain-life relationship, 'model F' *should* be applicable on fatigue analysis of aluminum. Application of 'model F' on aluminum requires, however, to change the size limits of the elements. This is needed due to its different micro-structure compared to steels. To check the applicability of 'model F' on fatigue analysis of aluminum should be one of the extensions of this study.

It was stated in previous paragraph that 'model F' should be applicable on fatigue analysis of all materials whose fatigue behavior can be characterized by strain-life relationship. Table 5.3 gives the *approximate* limits on material constants of strain-life relationship for commonly used steels and aluminum alloys. Thus, this table indicates a huge *possible* application range of 'model F' which in the frame of this study has remained mostly unchecked. Summarily, 'model F' *should* be applicable on fatigue analysis of very large range of materials, but in cases not verified in this study, the model must be calibrated (on element size δ, for example) and checked before applying it.

Constant	E [N/mm²]	σ'_{ys} [N/mm²]	n'	K' [N/mm²]	σ_f' [N/mm²]	b'	ε_f'	c'
Upper limit	230000	600	0.25	1500	1500	-0.05	3	-0.2
Lower limit	60000	100	0.05	500	300	-0.15	0.05	-1

Table 5.3 : *Approximate limits on material constants used in 'model F'.*

Detail geometry. 'Model F' has no restrictions on detail geometry - the model can be applied to fatigue analyses of details of *any* geometry, provided that the distribution of the stress concentration factor *SCF(x)*, and the stress intensity correction factor *Y(a)*, are known. The effects of plate thickness are taken into account by the plastic constraint factor *pcf*, where *pcf* varies between 1 and 3.

Loading. 'Model F' can be applied to fatigue crack propagation simulations under *any* constant amplitude loading. *Any* variable-amplitude loading history can be analyzed by 'model F' if the fatigue life of the element is less than one million cycles (condition 5.22). If the fatigue life exceeds one million cycles, then the results predicted by the model are uncertain. In latter case, 'model F' needs further verification.

The absolute maximum and absolute minimum nominal stresses in the load history must satisfy conditions (5.21) and (5.22) correspondingly. These conditions are determined by assumptions and principles made and established in the crack closure model. In addition, nominal loading must not cause a large scale yielding of the section (condition (5.20)).

$$\sigma_{0,max,abs} \leq 0.8 \cdot \sigma'_{ys} \tag{5.21}$$

$$\sigma_{0,min,abs} \geq -\sigma'_{ys} \tag{5.22}$$

Residual stresses. 'Model F' allows to analyze the influence of *any* distribution of fabrication-introduced residual stress on fatigue behavior.

5.7.2 Advantages and Disadvantages

The *advantages* of the 'model F' are :

- 'Model F' allows to simulate the crack initiation life as well as stable crack growth life. Therefore, both important crack propagation stages : the crack initiation and the stable crack growth, are considered.
- 'Model F' takes into account a very wide range of fatigue parameters such as variable-amplitude loading, any geometry of detail, structural steels as material, and fabrication-introduced residual stresses - almost all important fatigue parameters are considered (only environmental effects are excluded).
- 'Model F' takes into account the interaction of fatigue parameters. This interaction results various aspects of fatigue crack propagation such as fatigue threshold, small crack behavior, crack closure effect, variable-amplitude load effects, specimen thickness effect, crack behavior under cyclic compression. All mentioned aspects are considered by 'model F'.
- Verifications showed that 'model F' is generally able to simulate the fatigue behavior under conditions given above. The only case where a discrepancy between simulation and test results was observed is the case when fatigue life of element under variable-amplitude loading is between 1 and 4 million load cycles.
- Parametric study showed that numerical parameters have small influence on simulation results. This demonstrates that modeling principles were chosen successfully - the influence of fatigue parameters on simulation results is not erased by the influence of numerical parameters.

The *disadvantages* of 'model F' are :

- since the fatigue analysis is carried out using the material's *average* data, security factors should then be applied on the simulation results, if used in fatigue design. The calculation of the security factors is out of the scope of this study.
- A great amount preliminary efforts are needed to put the proposed model into the computer code. 'Model F' includes a number of complicate calculation algorithms. In most cases calculation procedures are iterative and not linear. This complexity implies a need to simplify the algorithms of 'model F' in order to make the model more easier to use. In the

same time, all features and aspects 'model F' considers should be included also into simplified model.

5.8 SUMMARY AND CONCLUSIONS

Parametric Study

The influence of four groups of parameters on crack initiation and on total fatigue life were studied. The four groups of parameters included: *numerical* parameters, *material* parameters, *detail geometry* related parameters, and *loading* parameters. Based on the results of a parametric study, these parameters can be classified into four groups according to their influence on fatigue behavior :

1. parameters with a *very large* influence :
   - nominal stress range $\Delta\sigma_0$;
   - the distribution of the stress concentration factor $SCF(x)$;
2. parameters with a *large* influence :
   - the ratio of minimum and maximum nominal stress R ;
   - the distribution of the residual stress $\sigma_{res}(x)$;
   - variable-amplitude loading history compared to the use of equivalent constant-amplitude load range ;
   - constants of the strain-life relationship : σ_f', b', ε_f' and c' ;
   - steel type ;
3. parameters with a *moderate* influence :
   - constants of Ramberg-Osgood Equations (3.49) and (3.48) : n' and K' ;
   - use of the Neuber's rule instead of Glinka's ESED criterion ;
   - element size δ;
4. parameters with *small* or *no* influence :
   - elastic modulus E ;
   - the crack tip radius ρ ;
   - cyclic yield stress σ'_{ys} ;
   - the number of local elements used at the same time in calculations n_{local}.

It can be concluded that numerical parameters, compared to other parameters studied, have a small influence on fatigue behavior. This reconfirms that the modeling approach is reasonable and reliable since numerical parameters will not significantly influence the results obtained from the model.

Discussion of 'model F

A brief discussion of 'model F' was made. Based on the results of the quantitative and qualitative comparisons, as well as on the results of parametric study, the application limits of the model were established. In addition, the advantages and disadvantages of the model were outlined. It appears that the range of application for 'model F' is large compared to existing fatigue models. The negative aspect of 'model F' is that it is complicate to realize.