7. CONCLUSIONS

This chapter concludes the study carried out under the theme : 'extended numerical modeling of fatigue behavior'. It summarizes the results regarding the goals in the introduction (Chapter 1) and the original aspects of the study, and outlines possible directions of the future work.

7.1 RESULTS

Fatigue Model

The main result of this study is the creation of an algorithm and numerical model which simulates fatigue behavior of structural details. This model is called 'model F' and is based on the fatigue analysis of elements situated along the crack propagation path. Crack propagation is modeled as gradual damaging and failure of these elements, calculated as a function of the elastic-plastic cyclic strain range i.e. the response of elements on fatigue loading. The elastic-plastic cyclic strain range is computed as a function of the linear-elastic cyclic stress range applied to the elements and the stress concentrators.

A new crack closure model was developed. It is a portion of 'model F' and is based on the analysis of an opening displacement of a Dugdale crack. The crack closure model provides methods to calculate the opening stress intensity factors and therefore can account for the effects of variable-amplitude loading on fatigue behavior. The crack closure model was determined using an original method compared to existing yield strip models. This method is advantageous because it leads to a much faster calculation of crack opening stress intensity factors than conventional yield strip models.

Analysis of the Model

The developed fatigue model - 'model F' was analyzed by comparing results obtained from simulations to actual fatigue test data. A parametric study of input parameters using the model was also carried out. The analysis was used to obtain the advantages and disadvantages of 'model F'.

The first advantage of 'model F' compared to existing fatigue models is that it provides a method to calculate the crack initiation life *and* the stable crack growth life. The existing fatigue models need *individual* distinct approaches to be applied for the crack initiation and the stable crack growth. In 'model F', both the crack initiation life *and* the stable crack growth life are calculated using a *similar* method that is in agreement with the propagation of physical crack : material damage at the crack initiator is qualitatively the same as material damage at the fatigue crack tip.

The second advantage of 'model F' is that it accounts for many fatigue parameters. Considerably more than the number of parameters considered by existing models. In addition, 'model F' takes into account the *interaction* of these parameters. Considering the interaction of fatigue parameters enables the model to simulate all important aspects of fatigue crack propagation such as variable-amplitude related load effects, fatigue threshold, behavior of short fatigue cracks, effects of plate thickness, and crack initiation and stop due to cyclic compression. In summary, 'model F' can be used for crack propagation simulations of steel specimens of *any* geometry with *any* distribution of residual stresses, and that is loaded by *any* nominal loading history.

The disadvantages of 'model F are as follows. First, comparisons with test data showed that 'model F' may be non-conservative if the fatigue life of elements under variable-amplitude loading situates between 1 to 4 million cycles. The reasons of this non-conservatism may possibly arise as a result of using the linear damage accumulation rule, a large scatter of material properties etc. More comparisons are needed to clarify this controversy. The second disadvantage of the model is that it is a relatively complex computer program. The reasons of complexity are that the algorithms of ‘model F’ contain a number of iterations.

The application limits of the model were reviewed in Section 5.2, including limits due to theoretical assumptions and limits on input data. The principal theoretical requirement of the model is that cyclic behavior of material in the plastic zone at the stress concentrator must be controlled by the elastic behavior of the material surrounding the plastic zone (small scale yielding requirement).

Classification of Fatigue Parameters

Based on the results of the study of parameters considered by ‘model F’, the parameters analyzed were classified by their influence on the fatigue behavior. It was found that parameters of :

- *very big* influence are - the nominal stress range $\Delta\sigma_0$, - and the distribution of the stress concentration factor $SCF(x)$;
- *big* influence are - the ratio of the minimum and maximum nominal stress R, - the distribution of fabrication-introduced residual stress $\sigma_{res}(x)$, - variable-amplitude loading history, - the constants of the strain-life relationship σ'_f, b', ε'_f, c', - and the steel type ;
- *medium* influence are - the constants of Ramberg-Osgood equation K' and n', - and plastic constraint factor pcf ;
- *small* and *no* influence are - elastic modulus E, and - cyclic yield stress σ'_{ys}.

The classification of parameters given above, agrees well with that obtained experimentally by other studies.

Simplification and Application of the Model

A crack propagation rate equation was developed based on the principles used in ‘model F’. This equation leads to similar results to those obtained using the Paris equation, but has the following advantages :

- the constants of the crack propagation rate equation can be determined without testing : they can be calculated using the material parameters of the strain-life relationship and Ramberg-Osgood equation ;
- the developed equation provides a method to account for the fatigue threshold without introducing an extra parameter ;
- the developed equation provides a method to account for the effect of the maximum stress intensity factor K_{max} on the crack propagation rate.

Simplified fatigue model - ‘model SF’, was created on the basis of ‘model F’ in order to simplify the realization process (programming). The ‘model SF’ is based on proposed crack propagation rate equation and can be used to calculate the crack initiation life *and* the stable crack growth life. ‘Model SF’ takes into account the same range of fatigue parameters as ‘model F’ as well as the interaction of these parameters. Therefore, ‘model SF’ can be applied for the fatigue analysis of steel specimens of *any* geometry, containing *any* distribution of fabrication-introduced residual stress, loaded by *any* nominal loading history. The advantage of ‘model SF’ compared to ‘model F’ is that it is simpler. On the other hand, ‘model SF’ leads to more conservative predictions of fatigue behavior than ‘model F’. It should be mentioned that a more in depth verification of ‘model SF’ is needed.

The model should be applied and combined with fatigue testing. In other words, the most important parameters can be first selected using the model and fatigue tests can then be carried out varying the selected parameters only. This should lead to a remarkable decrease in testing time.

7.2 ORIGINAL ASPECTS OF THE STUDY

Fatigue Crack Propagation Model

Fatigue crack propagation models based on the damage and the failure of the elements was already discussed by Glinka, who attempted to calculate the stable crack growth life using a similar method. The original portion of this study is that both, the crack initiation and the stable crack growth stages are covered by the method similar of that of Glinka, and the criterion allowing to differentiate between these stages was introduced. In addition, the model developed takes into account the influence of many more parameters than the model of Glinka (see paragraph 'Scope of Modeling' later in this section). The second original aspect of the 'model F' is that it considers simultaneous damaging of the area around stress concentrator.

Crack Closure Model

Modeling of crack closure phenomenon includes four aspects original to this study :

- the development of generalized equations for dynamic behavior of a Dugdale crack.
- A crack closure model, based on the dynamic analysis of Dugdale crack that takes into account the influence of the plastic zone and the plastic strip on the crack closure.
- Equations used to calculate the stabilized values of crack opening stress, σ_{op}^*, and the crack opening stress intensity factor, $K_{op}*$.
- Equations used to take into account the change in σ_{op} and K_{op} as a function of crack length a.

Crack Propagation Rate Equation

Crack propagation rate equation, as well as formulas to calculate required constants, are also original to this study. The equation takes into account the influence of the effective stress intensity factor range ΔK_{eff}, fatigue threshold and maximum stress intensity factor K_{max} on the crack propagation rate da/dN.

Range of Parameters

Finally, the range of fatigue related parameters covered by 'model F' should be mentioned as an original aspect of this study : the 'model F' is applicable on analysis of large variety of fatigue problems. The range of the input data covers most commonly occurring cases. 'Model F' takes into account both the crack initiation and stable crack growth stages. In addition, all important aspects of fatigue behavior are included : crack closure effect which permits the influence of variable-amplitude loading to be considered, fatigue threshold, small crack behavior, specimen thickness effect, and crack behavior under cyclic compression.

7.3 FUTURE WORK

7.3.1 Study of Fatigue

Future applications of the model can be :

- Study of the material parameters. A wide range of material properties were included in the model. It was shown that the constants of the strain-life relationship have a large influence on fatigue behavior. The materials should be classified by their fatigue properties so that engineers can choose the steel depending on its fatigue properties. Fatigue codes differ between materials using material monotonic parameters such as yield stress and the ultimate tensile strength, and not their fatigue properties. It is possible however, to obtain a large gain in fatigue life if an adequate material is chosen to carry the fatigue loads.

– Study of the influence of detail geometry. The distribution of the stress concentration factor was shown to have the second largest influence on the fatigue behavior. The ‘model F’ allows to study the influence of the geometry of a very large range of details. It was shown that the *crack initiation* life can be normalized using the multiplication of the nominal load range *and* the stress concentration factor : $SCF^{*} \cdot \Delta\sigma_0$. It appears that a similar normalization could be done for the *total fatigue life* if the nominal load range and the *distribution* of the stress concentration factor are used. This would allow details to be generalized or classified by their geometry . A further study is needed in order to find out of how *and* which parameters of the distribution of the stress concentration factor influence the length of the stable crack growth stage.
– Study of the influence of variable-amplitude loading.

7.3.2 Development of the Model

Two directions for the future development of the ‘model F’ can be outlined :

1. Further extension of the possibilities of the model in order to generalize and enlarge it's applicability (development of the substance) include the following topics: - multi-axial fatigue, - the third stage of the crack propagation (unstable crack growth), - closure mechanisms other than those that are plasticity induced (e.g., oxide or roughness induced crack closure), - the mode II and III crack propagation as well as mixed mode crack propagation, - possibility to consider statistical aspects of the input parameters (variation of the material properties). The range of applicability of the model also needs to be further studied : the differentiation criterion between the crack initiation and the stable crack growth stages should be confirmed by experiments, and the sensitivity of ‘model F’ to the mechanisms of fracture, analyzed.
2. An improvement of the user interface in order to make the model easier to use by creating a graphical input module which makes the input of the initial data easier (development of the form),. For example, a user will not have to introduce geometrical data in terms of stress concentration factors and stress intensity correction factors. The input module should contain a graphical library of the typical details and cracks from which a user could select the needed geometry. Creation of a graphical output module would also make the analysis of the simulation data easier. Creation of the dynamic link libraries of the modeled objects facilitates the development of the model by other programmers (it is possible to add the ‘model F’ to the post processor of some finite element program, for example).