ASSESSMENT OF FATIGUE CRACK RATE UNDER CYCLIC LOADING

Assistant Lecturer: Muhanad Hamed Mosa
University of Al-Qadisiya, College of Engineering, Department of Mechanical Engineering
Email: alafaq_eng@yahoo.com
Received 7 April 2014 Accepted 21 May 2014

ABSTRACT

Fatigue crack growth (FCG) in structures subjected to variable amplitude (VA) loading is a complex phenomenon. Analysing of FCG rate is important for the reliable life of engineering structures. It is difficult to model all the parameters influence FCG correctly due to the random nature of the VA loading as well as the number and complexity of the mechanisms involved in the FCG problems. . It has been found from the literature review that no universal model has been developed to analyse the crack growth condition under VA loading. In addition, no general understanding has also been agreed among researchers for any available models. Therefore, the main objective of this work is to investigate the FCG under VA loading based on FCG models also to propose a suitable model for VA loading. The work describes some of the FCG models for predicting the fatigue lives and FCG rates. For the simulation part of this study, towards prediction of crack propagation under cyclic, variable and random loading were used. The results had been carried out based on the Austen, modified Forman and NASGRO models. There are many factors affecting the FCG, which shown with great influence such as; initial crack length, load sequence, aspect ratio and stress ratio.

Keyword: Fatigue crack growth (FCG), variable amplitude (VA), finite element method (FEM)

INTRODUCTION

The phenomenon of fatigue has been discovered in the post-incident findings of the Versailles incident in 1842. Since then, engineers and scientists have developed models to predict the fatigue life of components and to incorporate the fatigue analysis in the design. When pressure vessels and piping are subjected to fluctuations in stress, they may lead to the development of fatigue cracks. Fatigue cracks extend slowly, and this is generally with a very small increment of crack growth occurring with each cycle, and with little or no evidence of plastic deformation. The cracks can continue to grow until they completely cause failure of the component, member or structure by fast fracture, plastic collapse or other mode, which prevent service duties being performed. The service load histories may completely in random pattern. It is either to be simple and repetitive or at the other extreme. In general, prediction models published in the literature employ basic material fatigue data as references. Such data can be fatigue limits, stress-life (S-N) data, fatigue diagrams, crack growth data, and fracture toughness for the final failure. These prediction models that are used for crack growth under variable amplitude (VA) loading vary from simple modifications on the constant amplitude (CA) baseline up to the complex models with detailed descriptions of relevant fracture mechanisms. For instance, some models calculate crack growth by averaging over the applied load spectrum, while many others tend to calculate it using the cycle-by-cycle analysis. Despite the on-going development of the prediction models towards a more accurate description of the phenomena, there seems to be no general agreement about which mathematical description is the most useful. In fact, the simplest prediction models are still being used by many engineers. The alternative to make prediction is to carry out experiments for specific fatigue questions when they arise. Unfortunately, testing is not always possible due to geometry complication, time, costs etc (Simonsen & Tornqvist 2004; Richard et al. 2008).

This is even complicated by the fact that it is not at all easy to accomplish experimental fatigue conditions which will give a relevant answer to the question raised. Thus, the overall fatigue life of a component is generally defined as follows: “Total life = Initiation life + Propagation life”. This can be represented in a block diagram of Figure 1.1.

The prediction of fatigue properties of structures and avoiding structural fatigue were recognised as engineering problems in the early decades of the 20th century. High stress concentrations were understood and taken as possibly harmful and should therefore be avoided. The significance of stress concentration factors had been identified before 1950 and designers also realised that the fatigue performance of a structure was dependent upon improved detail design (Schijve 2003). In 1950s, many investigators mentioned how early in the fatigue life they could observe microcracks. Since then, it has been clear that the fatigue life under cyclic loading consists of two phases, namely the crack initiation life, followed by a crack growth period until failure (Khan et al. 2004).

Predicting fatigue crack growth in metals under random loadings is a difficult task, particularly because of the load history effects, which are known for decades to stem from plastic deformation in the vicinity of the crack tip (Schijve 1999; Skorupa 1999; Hamam et al. 2007). In addition, history effects are closely related to the elastic–plastic behaviour of the material. Although many fatigue crack growth (FCG) models have been developed, none of them enjoys universal acceptance. Each model can only account for one or several phenomenological factor(s).

From an engineering point of view, the experience of dealing with fatigue problems in the beginning of the previous century was still a matter of trial and error. In later decades, however, continued research (Schijve 2003; Huang et al. 2005) clearly indicated, that the number of variables that could affect the fatigue strength and the fatigue life of a structure is large. In principle, it is correct to consider fatigue as a phenomenon, which is characterised by microcrack initiation, crack growth as an invisible microcrack, and later as a visible macrocrack which finally leads to a complete failure. Unfortunately, this concept does not mean that the fatigue phenomenon occurs in the same way in all metallic materials (Schijve 2003).Though many damage models have been developed, none of them enjoys universal acceptance (Fatemi & Yang 1998; Paris et al. 1999; Molent et al. 2008). Each damage model can only account for one or several phenomenological factors, such as load dependence, multiple damage stages, nonlinear damage evolution, load sequence and interaction effects, overload effects, small amplitude cycles below fatigue limit and mean stress. Due to the complexity of the problem, none of the existing predictive models can encompass all of these factors. Therefore, the applicability of each model varies from case to.

Fracture mechanics seeks to establish the local stress and strain fields around a crack tip in terms of global parameters such as the loading and the geometry of the structure. The fracture mechanical approaches are usually divided into linear elastic solutions and non-linear methods.

For linear elastic materials, Irwin (1957) suggested describing the stresses in the vicinity of the crack by stress intensity factors (SIFs). There are basically three different types of SIFs, with each describing one of the deformation modes illustrated in Figure 1.2. The superposition of these three modes forms the general case of cracking. Meanwhile, the deformation modes can be characterised as follows:

(a) Mode I: The in-plane tensile mode where the crack surface is symmetrically opened,
(b) Mode II: The sliding or shear mode which is present when the crack is exposed to skew-symmetric in-plane loading,
(c) Mode III: An anti-plane mode where the crack surface is twisted by forces perpendicular to the crack plane.

In the simulations of crack propagation in linear elastic fracture mechanics (LEFM), it is usually the combination of modes I and II which is of greatest interest. Irwin (1957) analysed this in-plane mixed mode problem, and using the Westergaard (1939) stress functions, he found an analytical solution for the stress distribution in the vicinity of the crack tip.

SIMULATION OF FATIGUE CRACK GROWTH

Assessing the behaviour of fatigue cracks in any structure is a complex and uncertain process due to the large number of parameters that may influence the crack growth process. For instance, pipes or tubes contain defects from the manufacturing, installation and servicing processes. The defects can affect the safety of the structures, and even depress their service life that may lead to enormous economic costs and jeopardise the surrounding ecological environments. Numerous models have been developed over the past few decades and these have taken different approaches to modelling FCG; however, no universal or all-encompassing model exists. Most models are developed for a specific application and they incorporate the main parameters influencing FCG for the structure in question. A successful model is like a balance between being able to accurately predict the crack growth rate and its simplicity. Such a model is beneficial in planning inspection intervals, determining required maintenance and minimising the problem of crack propagation in any future designs.

The fatigue life prediction has brought significant advantages to designers, not least of all the abilities to do up-front fatigue calculations long before a prototype available. However, the combination of the two technologies also poses challenges. The engineering need for prediction models and some of the CA and VA loading FCG models were discussed. In this chapter, the methodology to select three of these models (the Austen, modified Forman and NASGRO models) and the fatigue life and FCG prediction as well as the factors affecting it. Then, the experiments setting are presented so as to enable the readers to fully understand how this work is accomplished.

The start of a fatigue failure is a strictly local process and also depends on the dynamics of the system. It is important to highlight that the time history of stress or strain, at the exact location where a crack is going to start, is the critical factor whereas the general distribution of these parameters throughout the component is of secondary interest. Accurate measurement, data acquisition, analysis, and testing are among the key factors in the process of calculating structure performance. Most structures survive in a VA loading environment and a predominant failure mechanism under these conditions is fatigue. Exploiting fatigue knowledge and the use of computer-based analysis techniques, at an early stage in the design process, can dramatically reduce the developmental period. Therefore, the designer has the opportunity to estimate the effects of changing geometry, material and loading performance.

Many shell structures such as pressure vessels or pipelines, contain defects from the manufacturing and servicing processes. These defects can affect the safety of the structure and even depress their life; may lead to enormous costs and jeopardize the surrounding ecological environments. For fatigue life prediction (S-N), the finite element technique was used for modelling and simulating the case study of the shell as a cylinder with infinite length in three-dimensional mesh, as shown in Figure 1.3.Selecting the right techniques of meshing are based on the geometry, model topology, analysis objectives and engineering judgment. Triparametric solids with the topological shape of a brick or wedge can be meshed either hex or wedge elements. Any other form of the triparametric solid can only be meshed with tetrahedral (TET) elements. The auto TetMesh approach is a highly automated technique for meshing solid regions of the geometry. It creates a mesh of tetrahedral elements for any closed solid including boundary representation (B-rep) solid. Tetmeshing produces high quality meshing for B-rep solids model imported from the computer aided design (CAD) systems. Since the tetrahedral is found to be the best meshing technique, the TET4 (4 nodes tetrahedral) version of the cylinder head was then used for the initial analysis. In addition, the TET4 compared to the TET10 (10 nodes tetrahedral) mesh using the same global mesh length. The TET10 mesh is presumed to represent a more accurate solution since TET4 meshes are known to be dreadfully stiff. For this purpose, the finite element analysis technique, with tetrahedral elements (10 nodes) shown in Figure 1.4, was applied to model and simulate based on the MSC Nastran/Patran analysis codes (MSC 2005). In order to study the fatigue life prediction, a shell with $T/D < 0.1$ (where T is the thickness and D is the diameter) and $L/D > 10$ (where L is the length) was analysed.

The cycle-by-cycle analysis can be performed with or without involving interaction effects, i.e. the effects of a load cycle on the crack growth in later cycles. Both the constant and random amplitude loadings are shown in Figure 1.5. For the VA loading, similar programmable VA load histories, as given by with different values, were used in the analysis with different load sequences and values ranging from high to low or from low to high, as shown in Figure 1.6. The presence of the interaction effects is always altering the crack growth rate, under the application of the VA loading. In order to correctly predict the crack growth under VA loading, it is necessary to involve the interaction effects, while developing the prediction models, as a part of cycle by cycle analysis using different models. The CA loading has been developed to correlate FCG rates for different values.

The steel used in the fabrication of pressure vessels is usually of two kinds, viz. carbon steel and alloy steel. In the pressure vessel steel, carbon is of prime importance because of its strengthening effect. It also raises the transition temperature, lowers the maximum energy values and widens the temperature range between completely brittle behaviour. Manganese (up to 1.5%), on the other hand, improves low temperature properties (ASM 1993). Of all the different kinds of steel, those produced in greatest quantity fall within the low carbon classification. These steel types generally contain less than 0.25 wt. %C and are unresponsive to heat treatments intended to form martensite, as strengthening is accomplished by cold work. Meanwhile, microstructure consists of ferrite and pearlite constituents. As a consequence, these alloys are relatively soft and weak, but have outstanding ductility and toughness, in addition to the fact that they are machinable, weldable and most important of all, steel is the least expensive to produce. They typically have yield strength of 585 MPa, tensile strengths between 637 and 825 MPa, and a ductility of 20-25 %EL. In particular, ASTM A533 is one such kind of steel which has applications in pressure vessels (ASTM standard V1.04).In this analysis, the material of the shell ASTM A533 steel has been used.

MODELLING AND SIMULATION

It is important to note that the fatigue life prediction based on modelling is very time consuming. For example, an off-shore platform designed to withstand 108 cycles in a 30 year life would require a 30 year test at 0.2 Hz to validate the design (MSC 2005). Computer-based prediction methodologies can perform the same validation with an equal accuracy in a very small fraction of the time (e.g. less than two hours) at a very small fraction of the cost. Such prediction software requires the fatigue crack growth to be accumulated on a cycle-by-cycle basis and it must also incorporate the complex effects of the stress history, crack closure, static fracture modes and notches and be able to predict the environmental influences on fatigue crack growth rates (corrosion fatigue). Stephens et al. (2001) have estimated that between 50% and 90% of these failure are due to fatigue. As a result of the recent advances in the finite element method (FEM) and its application to fracture mechanics, various numerical methods exist to calculate the fracture parameters and to evaluate the FCG models. One of the advantages of the numerical method is that accurate results can be obtained for complex problems of any geometry and crack configuration in a fraction of the time and cost, as compared to the alternative of experimentation.

Finite Element Approach

The start of a fatigue failure is a strictly local process and it is also one that depends on the dynamics of the system. The time history of stress or strain, at the exact location where a crack is going to start, is a critical factor and a general distribution of these parameters throughout the component is of secondary interest. This is precisely why the finite element analysis (FEA) is important in this particular discipline. With FEA, an analyst can choose any location within a model and concentrate on it. In fact, using FEA can give a tighter control over the move from general geometry and loading to the local parameters, and allows dynamic factors to be dealt with more analytically.

The concepts of fracture mechanics that were derived prior to 1960 are applicable only to materials that obey the Hook's law. Although corrections for small-scale plasticity were proposed as early as 1948, these analysis are restricted to structures whose global behaviour is linear elastic. Since 1960, fracture mechanics theories have been developed to account for various types of nonlinear material behaviour (i.e. plasticity and viscoplasticity) as well as dynamic effects. All of these more recent results, however, are extensions of LEFM. Thus a solid background in the fundamentals of LEFM is essential to an understanding of more advanced concepts in fracture mechanics. The linear static analysis was performed using the finite element software to determine the stress and strain. The finite element technique was used for modelling and simulation of the case study of the shell as a cylinder with infinite length in three-dimension mesh shown in Figure 1.3. For this purpose, the F technique with tetrahedral elements (10 nodes) shown in Figure 1.4 was being used for the modelling and simulating based on MSC Nastran/Patran analysis codes. To study the fatigue life prediction a shell with $T/D < 0.1$ and $L/D > 10$ (where T is the thickness, D is the diameter and L is the length) was analysed.The results of the maximum principle stresses and strains are used for the subsequent fatigue life analysis, using the cyclic load history (discussed above) as an internal pressure to the shell. Figure 1.7 shows the contour (image) of the stress distribution on the shell.

Software Codes

It is important to note that more than one software was used in this work for the modelling or the experiments. Firstly, the fatigue life predication (S-N) was performed based on the MSC Nastran/Patran software (MSC 2005). The crack growth software, developed by the nCode (2003), offers engineers the facilities to predict defect tolerant fatigue life based on all these aspects. These diagnostic techniques enable iteration and interpolation with different material, geometry and history inputs, as well as probably the most important variable, i.e. the initial crack size. As for the modelling part of this work, the Glyphwork software was used to predict FCG after building the block system of all parts shown in Figure 1.8.

RESULTS AND DISCUSSION

In general, the plastic-zone size at crack front increases as it grows in a metallic material under cyclic loading. At low stress-intensity factor levels, the plane-strain conditions should prevail as the plastic-zone size becomes large compared to thickness. The FCG life under CA loading, using three different FCG models (the Austen, modified Forman and NASGRO models) is shown in Figure 1.9. Based on the simulation results, the Austen model was found to give the lowest value of life, i.e. 35% less than the NASGRO model. On the contrary, the modified Forman model gave a better life than that by 20%, while the NASGRO model revealed a higher life, i.e. 128 x 103 cycles to failure. The differences in fatigue lives predicted are mainly due to basic theoretical background for each model. The effects of using different fatigue crack growth models on the fatigue crack growth rate are shown in Figure 1.10. The differences are related to the results presented in the a-N curves.

The modified Forman model is capable of describing region III of the fatigue rate curve as well as included the stress ratio effect, while the NASGRO model take into account the crack closure effect as well as the previous factors. The Austen model is including the crack closure effect and capable of representing data in region II same as the other two models. So the NASGRO model represents more factors than the other two models and gives better representation of the data.

CONCLUSION

The methodology of simulation and modelling as well as the cyclic experimental setting suggested clarifying the objectives of this work. The present research focused on studying FCG under variable and random loadings. The finite element modelling and analysis of pressure vessel or piping were utilised to predict stress-life. The factors affecting the S-N curve, such as mean stress, wall thickness, surface finish, type of elements and mesh size, were also presented. The TPB specimen of ASTM A533 steel material was used in the assessment study on FCG under different loading conditions, such as cyclic, variable and random loadings. Therefore, the emphasis in this study was more on the assessment of FCG under variable and random loadings, based on three different FCG models, namely, the Austen, modified Forman and NASGRO. It is important to note that different models give different fatigue lives. In order to validate these results, a set of experiments were performed under the same boundary conditions and they were then compared with the predicted values. More importantly, a good agreement was found between the findings in the present study and those in the previous research.

The regression technique was used and shown by the polynomial equations for each set of the experiments and the comparison revealed discrepancies as a result of different loading conditions. Among the factors affecting the FCG rate were initial crack length, stress ratio, aspect ratio and load sequence. The results also showed that increasing the initial crack length, stress ratio and aspect ratio would tend to minimise the fatigue life. For the cases of the load sequence effect, the number of blocks and the stress ratio has significantly affected the crack growth rate.

REFRENCES

Fatemi, A. & Yang, L. 1998. Cumulative fatigue damage and life prediction theories: a survey of the state of the art for homogeneous materials. International Journal of Fatigue 20(1): 9-34.

Hamam, R., Pommier, S. & Bumbieler, F. 2007. Variable amplitude fatigue crack growth, experimental results and modelling. International Journal of Fatigue 29: 1634-1646.

MSC. FATIGUE. 2005. User manual. Los Angles: MSC. Software Corporation.
nCode. 2003. User guide manual. ICE-FLOW cracks growth. V 2.0.

Molent, L., McDonald, M., Barter, S. & Jones, R. 2008. Evaluation of spectrum fatigue crack growth using variable amplitude data. International Journal of Fatigue 30: 119-137.

Paris, P.C., Tada, H. & Donald, J.K. 1999. Service load fatigue damage-a historical perspective. International Journal of Fatigue 21: S35-S46.

Richard, H., Sander, M., Fulland, M. & Kullmer, G. 2008. Development of fatigue crack growth in real structures. Engineering Fracture Mechanics 75: 331-340.

Simonsen, B.C. & Tornqvist, R. 2004. Experimental and numerical modeling of ductile crack propagation in large-scale shell structures. Marine Structures 17: 1-27.

Schijve, J.1999. The significance of fractography for investigations of fatigue crack growth under variable amplitude fatigue. Fatigue Fracture Engineering Material Structures 22 :87-99.

Schijve, J. 2003. Fatigue of structures and materials in the 20th century and the state of the art. International Journal of Fatigue 25: 679-702.

Skorupa, M. 1999. Load interaction effects during fatigue crack growth under variable amplitude loading- a literature review Part II: qualitative interpretation. Fatigue Fracture Engineering Material Structures 22(10): 905-926.

Skorupa, M. 2001. Load interaction effects during fatigue crack growth under variable amplitude loading- a literature review. Part 1: Empirical trends, part II: Qualitative interpretation. Fatigue Fracture Engineering Materials Structures 21: 987-1006.

Stephens, R.I., Fatemi, A., Stephens, R.R. & Fuchs, H.O. 2001. Metal Fatigue in Engineerring. 2nd Edition. New York: J. Wiley & Sons.

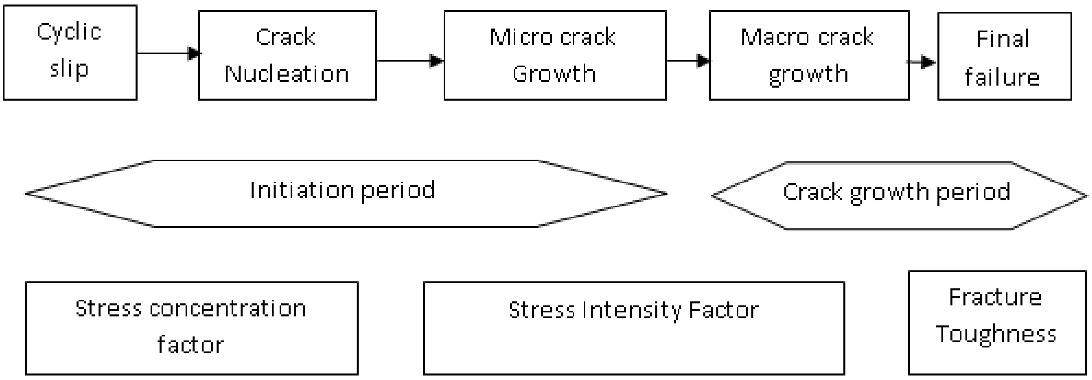


Figure 1.1 Different phases of the fatigue life and relevant factors

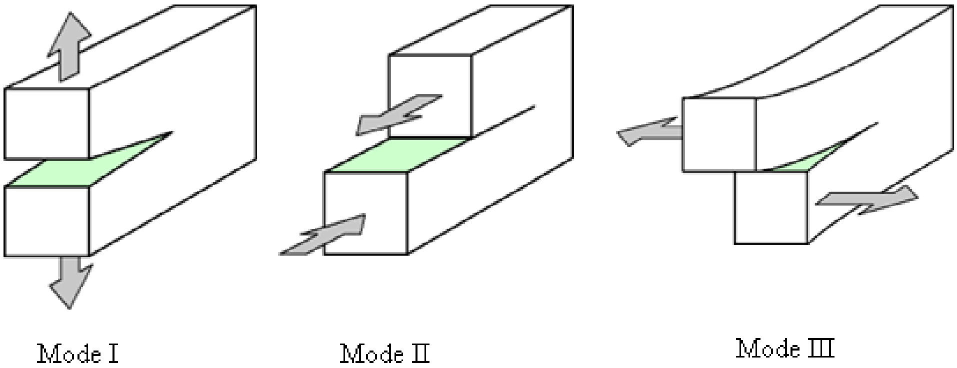


Figure 1.2: Three models of cracking Source: Anderson 2005

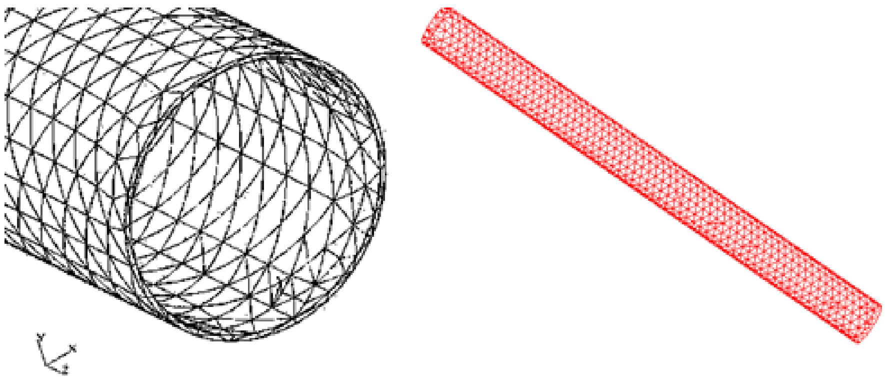


Figure 1.3: A finite element mesh of a shell structure

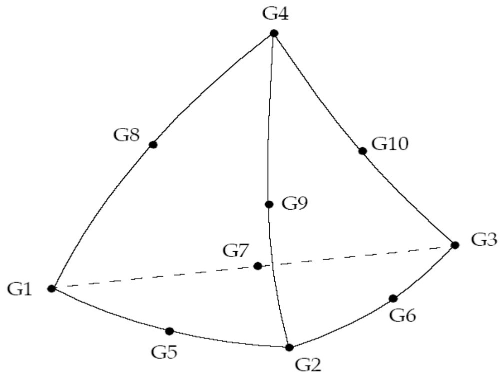


Figure 1.4: Integration grid points of the TET10 nodes

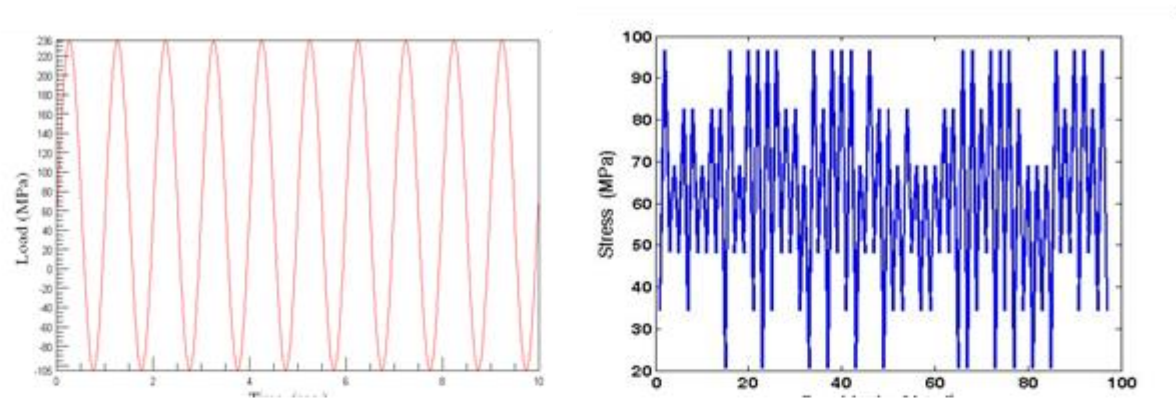
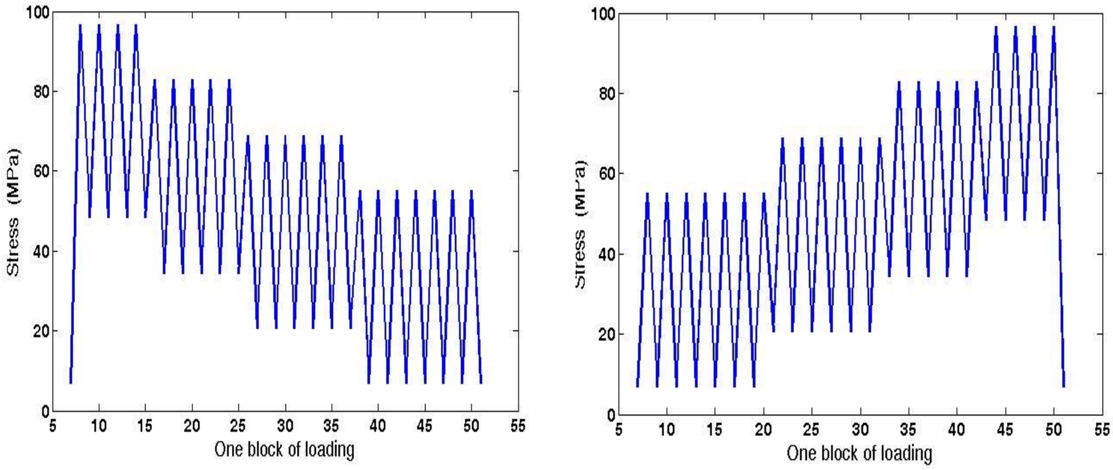


Figure 1.5: Display of constant and random loading



Case 1 Case 2

Figure 1.6: Display of the load histories with different two sequences

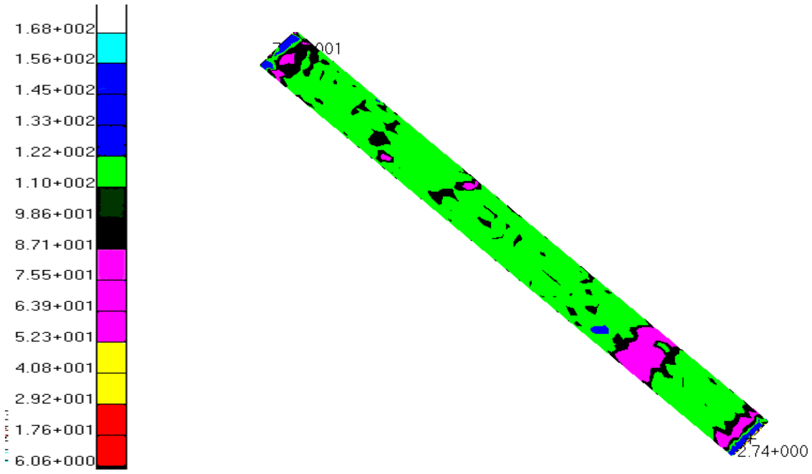


Figure 1.7: Contour displays of stresses on shell structure

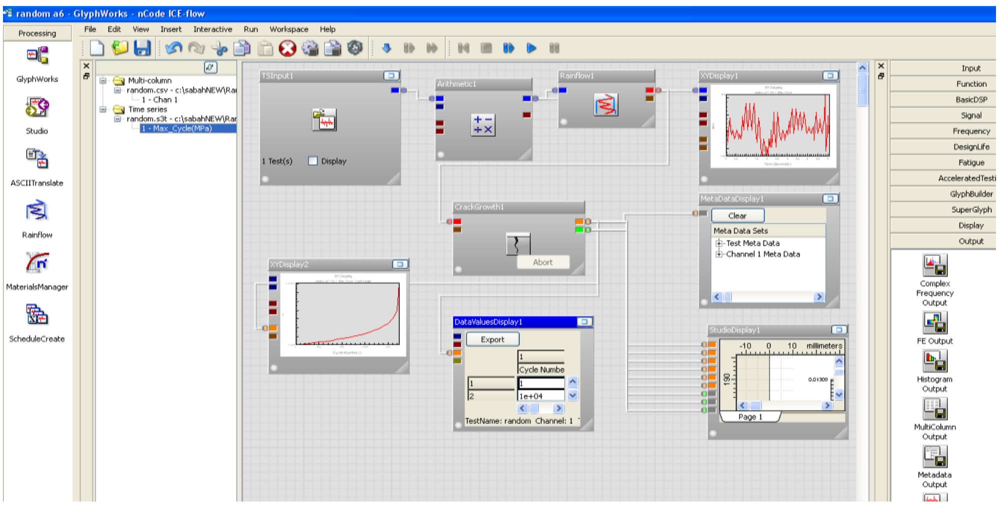


Figure 1.8: The FCG worksheet based on the Glyphwork softwareSource: nCode 2003

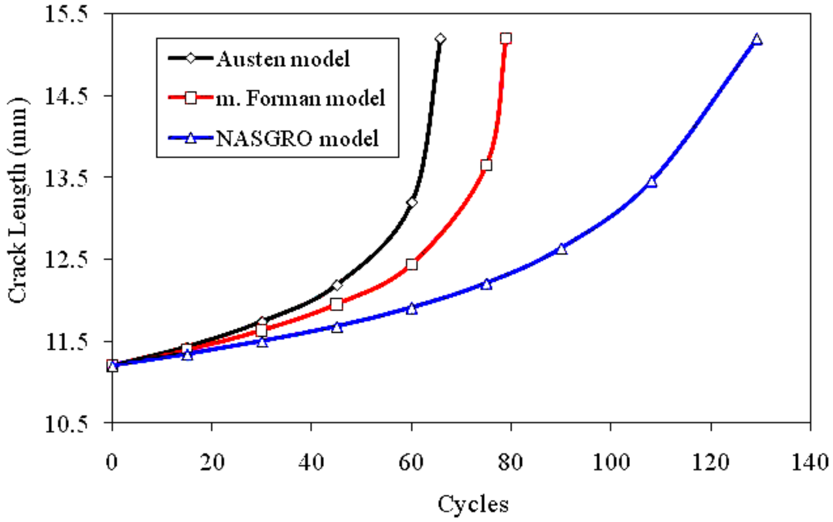


Figure 1.9: Fatigue crack growth using different models

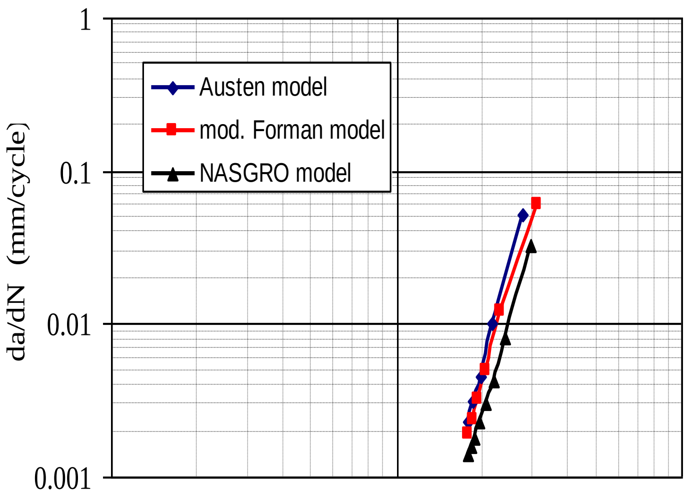


Figure 1.10: Fatigue crack growth rates for various TPB specimen geometries based on different FCG models