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FRACTURE MECHANICS EVALUATION OF POST YIELD FATIGUE CRACK INITIATION AND PROPAGATION

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ABSTRACT

A system of analytical and numerical solutions is developed to deal with fatigue crack initiation and propagation when local yielding occurs. The method is based on the detailed finite element analyses under spectrum fatigue loading. The finite element analyses are used to identify a shakedown condition where a stable residual stress field may be created after a period of fatigue loading. Under the shakedown condition, the analyses of fatigue crack initiation and propagation are performed based on a cycle-by-cycle crack growth evaluation according to a crack closure solution that accounts for both the small and long crack growth behaviour. In this way, the post yield fatigue crack initiation and propagation are evaluated.

KEYWORDS

Post-yield, fatigue, crack growth, strip yield model

INTRODUCTION

For many applications like mechanical or welded joints, local stress concentration is so high that plastic yielding may occur at a very low load level. Similar problems are encountered when residual stresses are introduced by production techniques. The residual stress may significantly increase the local stress such that yielding may occur under service loading. Since most engineering materials have enough resistance to yielding, a field of residual stress is often created to counter the local stress concentration. Significant fatigue life may remain even when local yielding occurs. Many structures are actually sized and used in applications where local yielding is prevalent. When structural weight is a concern, or welding or other advanced production techniques are used, the fatigue after local yield becomes an important issue. It is apparent that gross yield in structural details may prevent success of the use of fracture mechanics methods in evaluating crack initiation and propagation. So far, fatigue tests seem to be the only resort to deal with such a problem.

STRIP YIELD MODEL

When general material responses are considered under fatigue loading, three different cases may be considered as shown in Fig.1. The first case is for the stress less than the yield stress. A linear response will occur under fatigue loading as shown in Fig.1 (a). The second case is for the stress higher than the yield stress. An elastic shakedown state may occur if the range of stress cannot create repeated reverse yielding under fatigue loading. A residual stress field will be created to reduce the peak stress in the material. A linear material response may appear for the subsequent fatigue cycles. This case is an elastic shakedown case. For the third case, a plastic shakedown may be achieved if the material is subjected to large strain controlled fatigue loading, see Fig.1 (c).

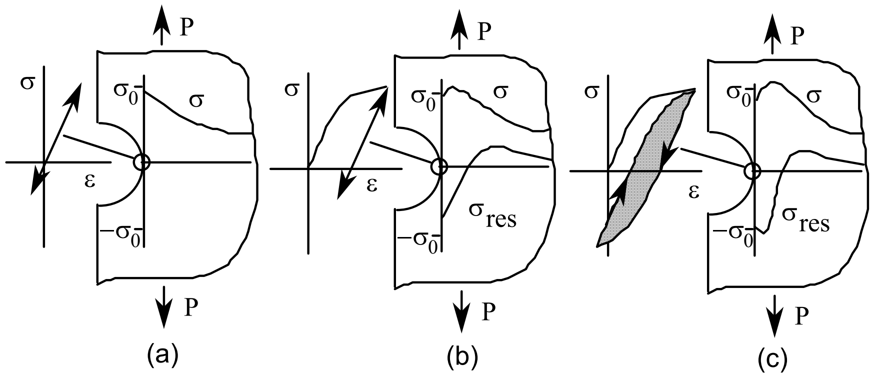


Fig.1: Schematic of various material responses under fatigue loading

Most of the post-yield fatigue problems in application involve the elastic shakedown condition as shown in Fig.1 (b). In this case, the fatigue problem may be solved according to fracture mechanics methods since fatigue life may be determined by considering a single and dominant crack initiation and growth. A possible solution is to consider fatigue crack growth in a residual stress field.

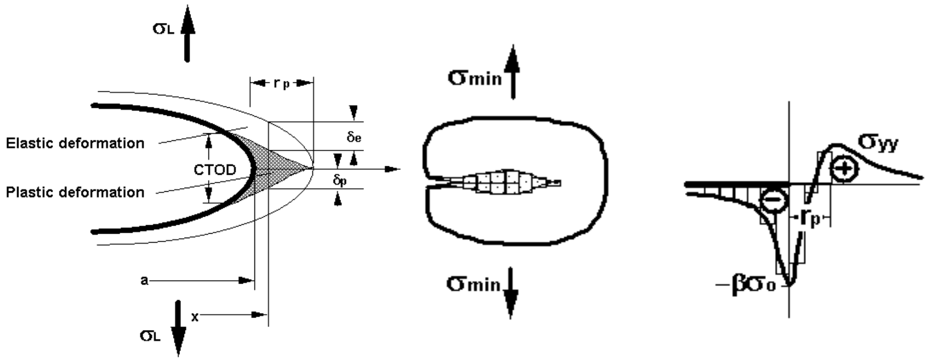


Fig. 2: Schematic of the strip yield crack closure model

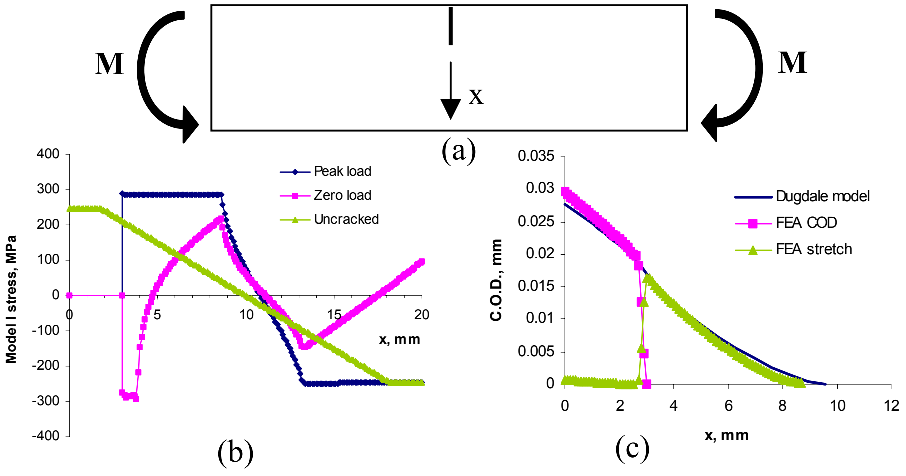
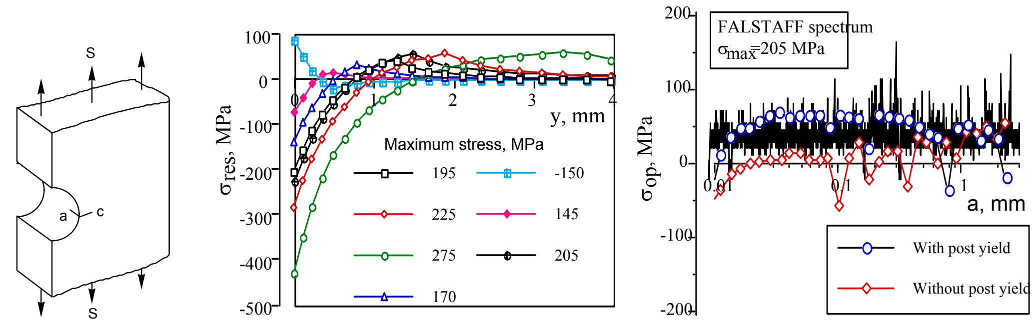


Fig.3: Non-linear finite element verification of the extension of the strip yield model for post yield crack problems.

The Elber's crack closure model [1] is one of the most successful models to account for various aspects of fatigue crack growth under general loading conditions. It may be extended to evaluate the post yield fatigue (PYF) problems. A strip yield model is a practical way to realise the crack closure analyses since the plasticity induced crack closure is often a dominant mechanism for most of the engineering materials, (Wang, 1993 [2]). The strip yield model, as shown schematically in Fig.2, is based on a strip yield assumption in the plastic zone [3]. By assuming an elastic crack located at the elastic-plastic boundary, the strip yield model is used to determine plastic stretches in the plastic zone so that a system of elements may be created to determine the crack closure, see Fig.2.

The strip yield model has been extended to solve the crack growth problems in residual stress fields created by the plastic yield (Wang, 1999 [4]). Fig.3 shows a verification of the strip yield model when gross yield occurs for a pure bending specimen, Fig.3 (a). Under a gross yield condition, see the stress curve with triangle symbols in Fig.3 (b), the non-linear finite element analyses (FEA) showed that the strip yield solution is a very good approximation for the plastic stretches in the plastic zone when a crack is created. Fig.3 (c) shows a comparison between the results of FEA and the strip yield model for the crack surface profile and pure plastic stretches in the plastic zone. When the plastic stretches are used in the strip yield model as shown in Fig.2, reasonably accurate solution of crack closure may be realised for the analyses of PYF problems.

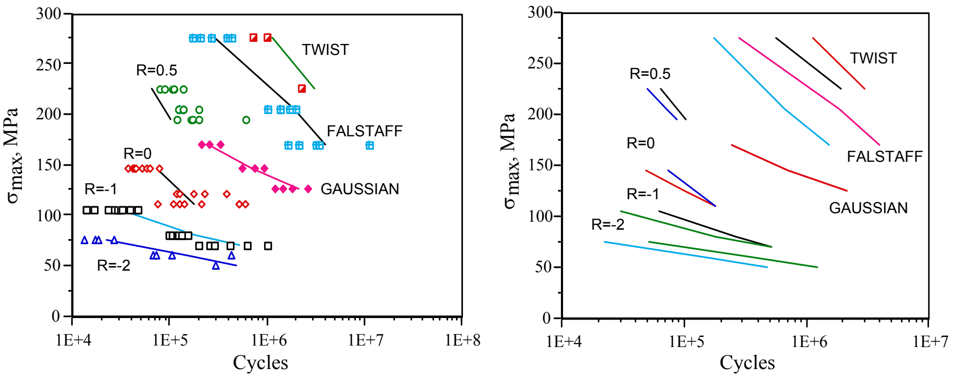


(a) (b) (c)

Fig.4: Residual stress analyses for a single notch specimen.

APPLICATIONS

To demonstrate the necessity and advantage of the PYF analyses, several cases are considered. The first case is for the fatigue life analyses of a single notch specimen, shown in Fig.4 (a), subjected to various spectra and load levels. Most of the fatigue load levels create plastic yield at the notch as shown in Fig.4 (b) for the resulting residual stresses. The PYF effect is particularly strong when a spectrum loading condition are considered. Fig.4 (c) shows an example of the crack closure solution for one case of FALSTAFF spectrum loading with and without post yield effect. When PYF occurs, the crack closure will occur at higher levels due to the residual compressive stress field created by the tensile dominant spectrum. The PYF affects strongly the fatigue life of many small load cycles. The fatigue life may be reduced, on the other hand, for a compressive dominant spectrum.



(a) (b)

Fig.5: Comparison of conventional and post yield analytical fatigue lives for various load and spectra.

Fig.5 shows predicted fatigue lives compared to test results for various fatigue load spectra and levels. There are reasonable agreement between predictions and tests, see Fig.5 (a). The PYF effect is obvious as shown in Fig.5 (b) (the curve close to the legends) compared to the analyses when the PYF effect is not considered (the curve away from the legends). The PYF effect can be positive or negative depending on the spectrum type (tensile or compressive dominant loading). For GAUSSIAN spectrum for example, the PYF effect is negligible since the spectrum is symmetrical at relatively high stress level.

PYF problems are not limited to high loaded details as the example as shown in Fig.4. Residual stresses in the detail may increase the local stress concentration and create PYF problems even when the applied load is low. An example is shown in Fig.6 for a type of cruciform welded specimens with different surface conditions [5]. The specimen has a rather high stress concentration at the as-welded state, but the stress concentration is low for the TIG-dressing condition. There are severe residual stresses due to the welding as shown in Fig.7 for the through-thickness residual stresses measured by the neutron diffraction method for different surface conditions.

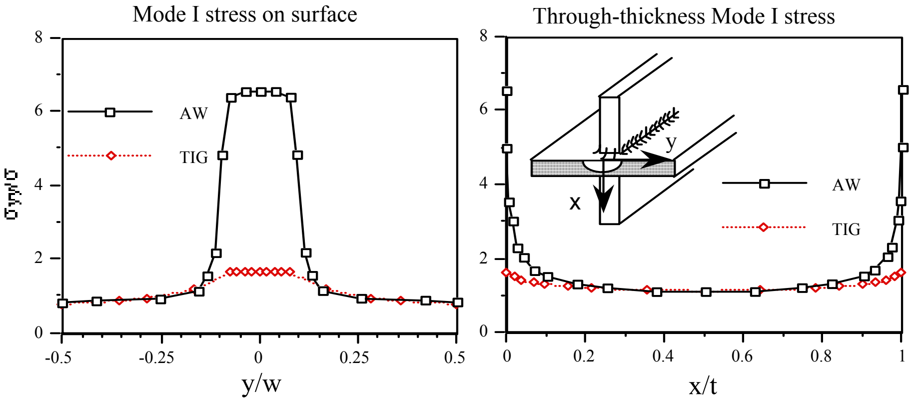
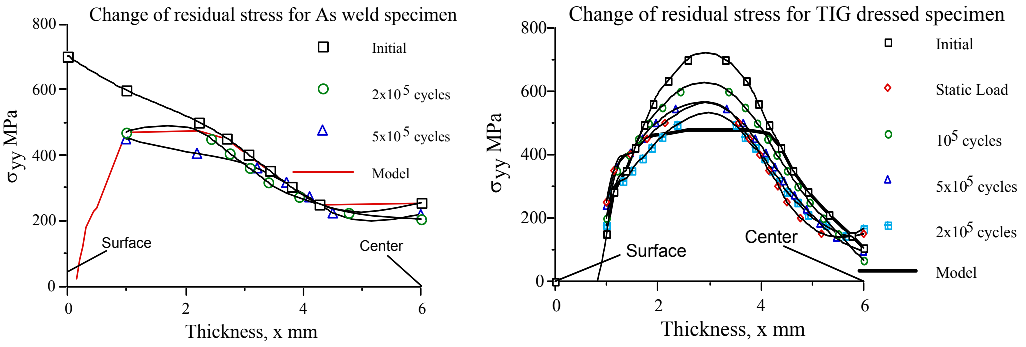


Fig.6: Stress concentration in a cruciform welding specimen.

Measurements of the same specimen after various fatigue cycles are also shown in the figure. The measurements, in agreement with the analyses, showed a possible elastic shakedown condition existing after the initial plastic yield, see Fig.7. At the shakedown condition, the stress concentration combined with the residual stress field creates a much stronger PYF effect as the fatigue results in Fig.8 shows for a comparison between various predictions and fatigue test results for a symmetrical spectrum loading condition. The fatigue lives are nearly two orders of magnitude shorter due to the tensile residual stress. Compared to the PYF effect as shown in Fig.5, the residual stress has a much stronger effect, see the comparison in Fig.8.

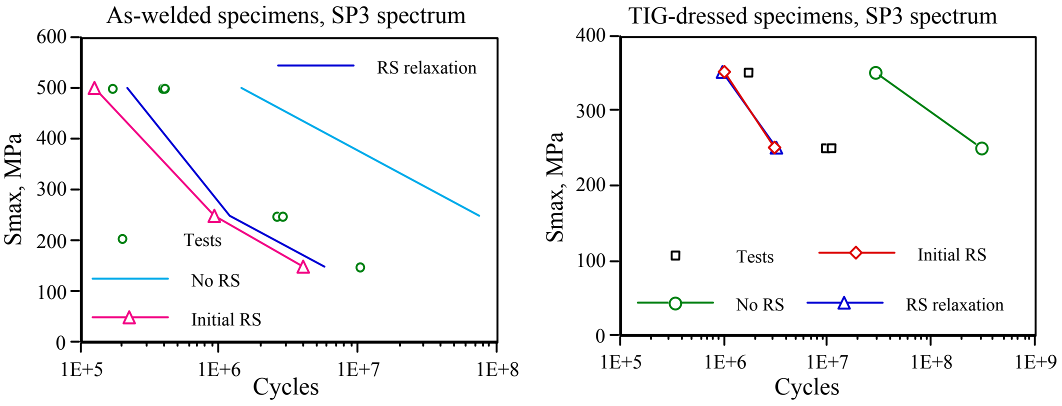


(a) (b)

Fig.7: Neutron diffraction measurements of residual stresses before and after fatigue loading at cruciform welding specimens for as-welded and TIG-dressing condition

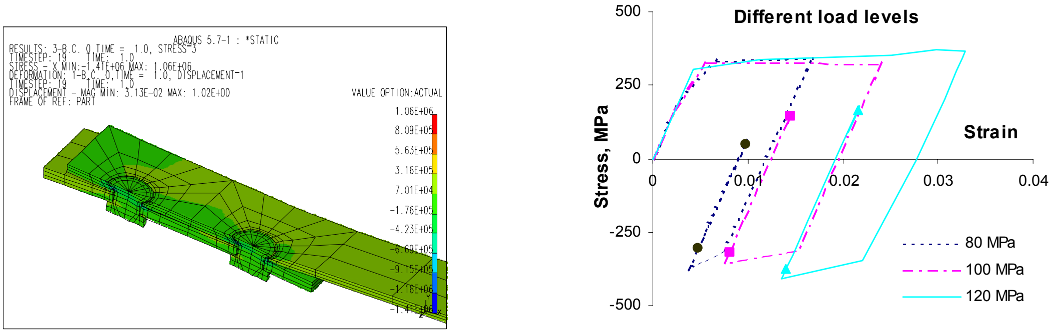
For a more complicate case when a mechanical rivet fastener joint is considered as shown on the right side of Fig.9 [6]. The fastener joint has not only a high stress concentration, contact and friction will also be strong at the joint. The right side of Fig.9 shows some stress-strain responses under the fatigue loading condition for various levels of fatigue loads. An elastic shakedown condition is observed in the finite element results even though the stress-strain behaviour is different.

Similar analyses are performed for the fatigue life analyses according to the shakedown stress condition. The analytical results are compared to the test results in Fig.10. In the same figure, the analytical results are also presented for a linear elastic fracture mechanics (LEFM) analysis based on forces computed from a simplified finite element model using shell and beam elements. It can be seen that there is a significant improvement in prediction capability when the post yield analyses are performed based on the stress analyses when critical fastener parameters are considered.



(a) (b)

Fig.8: Comparison of conventional and post-yield fatigue life analyses for as-welded and TIG-dressing condition for cruciform specimens.



(a) (b)

Fig.9: Shakedown condition at a rivet fastener joint for various load levels.

CONCLUSIONS

The consideration of post yield fatigue is necessary for complicate structural details that may involve plastic yielding under fatigue loading. Without the consideration, it is very difficult to evaluate fatigue problems based on fracture mechanics methods. Under the elastic shakedown condition, a strip yield crack closure model is extended to solve the fatigue problems due to its capability of dealing with load interaction and small crack growth problems. The model is based on the non-linear finite element analyses when cracks are not involved. Extension of the model to the post yield problems is demonstrated and verified with the non-linear finite element solutions. Several practical problems are presented to illustrate the solution and to verify its effectiveness. It is shown that with the correct solution, significant improvements, in at least one order of magnitude, may be achieved in evaluating fatigue life based on the fracture mechanics method even when gross local yielding has occurred. The method is significant in helping to understand fatigue behaviours in complex structural details when local yield occurs, and in promoting the fracture mechanics method into a much wider area of crack growth problems.

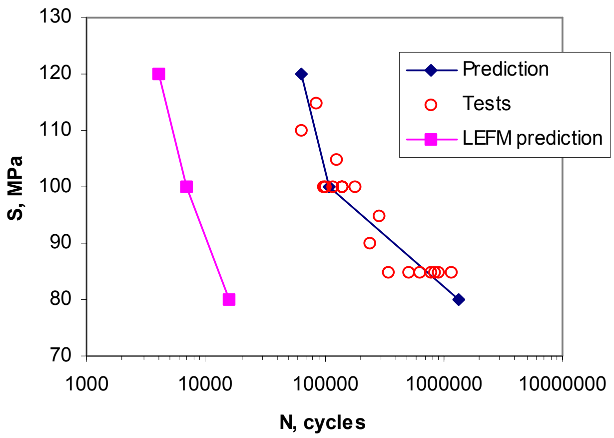


Fig.10: Comparison between analytical and test fatigue lives

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