

Crack Propagation Simulation with Material Deformation Memory Compensation

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Univ. of Windsor, Canada., Sept. 30 2013

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Abstract

In order to enable students and engineers to easily develop and extend existing crack propagation concepts, a set of programs has been developed, under the GNU General Public License, to provide a framework for further research. In this specific study the stress intensity factor adjustments for a surface crack projecting into a plate with a weld with both bending and membrane loads are modelled with a cycle counting code that is based on the behavior of a stress-strain model that incorporates material memory effects. The test history used contrasts the simulation of crack propagation with and without memory effect compensation.

Introduction

During cyclic loading processes in engineering structures, plasticity often occurs at local stress raisers. If the cyclic loading is variable amplitude in nature, the local plasticity will result in material memory events influencing the cyclic stress-strain path. Figure 1 shows a typical stress-strain path of an unnotched axial sample subjected to a strain controlled history in a servo-hydraulic test machine.

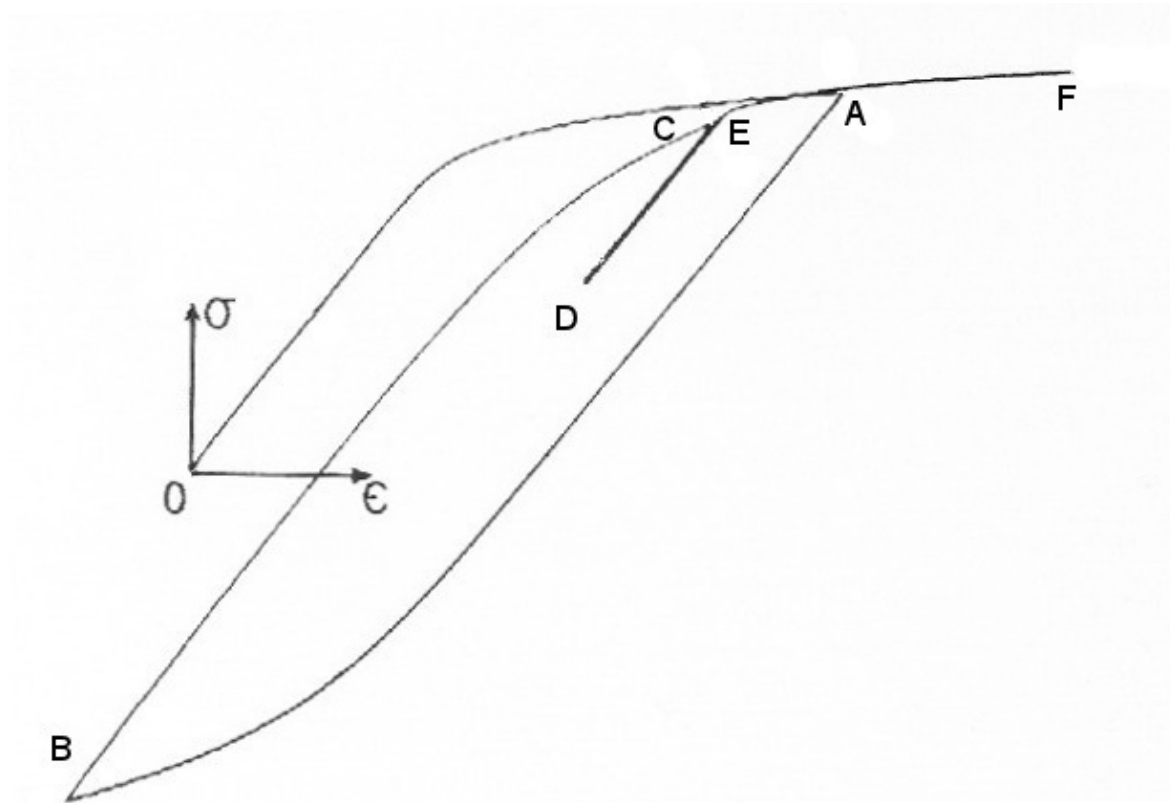


Fig. 1 : Movement of the stress strain locus during straining of cyclically stabilized aluminum

In the figure deformation and loading start at the zero strain and zero stress origin "O" and proceeds in tension along the monotonic curve to point A, where the deformation direction reverses towards compression and reverses again, in compression, at point B. From there the stress-strain locus moves in the tensile direction to point C where another reversal occurs and the locus moves to point D. From D the next half-cycle of strain moves all the way to F. Along this half-cycle however two memory events occur. The first is at E where the material remembers the old reversal point C and closes the small elastic hysteresis loop D-C. The second event is at the old point A where the hysteresis loop B-A is closed and the path of the stress-strain locus returns to the original monotonic path.

Such material memory events are occurring throughout any variable amplitude load or strain history imposed on a specimen or a component. The same behavior has been observed in un-notched axial samples, notched specimens, beams in bending, structural frames, and other components if one records the imposed load and the strain of a strain gage placed at any hot-spot on the component where there is plastic deformation [1]. The predictability of a material's memory has led to development of "Rainflow[2,5]" or "Push-Down List"[3] or "Reservoir[4]" In multiaxial loading conditions the C.C.Chu[6] and Mroz[7] stress-strain models use the same process or material memory model to simulate variable amplitude stress-strain behavior.

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It is expected that in the case of propagating cracks, where the loading is nominally elastic and plasticity is occurring near the tip of the crack, that material memory rules are also in effect, and must be accounted for in any simulation of the propagation events. In this study the memory event counting rules developed for non-cracked components are incorporated in a crack propagation model. The computations of stress intensity factors follow the guidelines set out in British Standard BS7910:2005 standard. The memory model logic is identical to that described in reference [3,8]. A little more detail is available in an F.D.+E. Comm. presentation [available here](#). For a complete review of the logic the reader is referred to the software listing. e.g.: [surface crack in plate plateWeldflaw.f](#) (click on "Raw" button to download)

Material

The steel used to demonstrate the functioning of the material memory propagation model was a A36 low carbon structural steel. The uniaxial stress-strain and fatigue properties are documented in one of the entries on the [Low Carbon steel page](#) in one of the F.D.+E. Committee databases. The merged A36 data set is a combination of results by Dindinger[9] and Miller[10].

Assumed Geometry

Although there are now a variety of program simulations using the features of this study, the present example is limited to a simple plate with a transverse weld feature subjected to both bending and membrane stresses with a semi-elliptical crack at the surface close to the weld. The dimensions as per BS7910 are:

```
# (All dimensions in mm)
#B= 10.0 # plate thickness
#W= 70.0 # plate width
#azero= 2.0 # initial crack depth
#czero= 4.0 # initial 1/2 crack width at surface
#L= 10. # Weld Feature width. Set to 0.0 if no Mkm or Mkb (weld)
```

Load History

The load or stress history is an artificial construct that contains the type of material memory events described in the introduction above. Also inserted, to test the software, are some non-reversal points which need to be eliminated prior to a simulation run. In the simulations the history peaks and valleys are magnified by a simple multiplication factor to increase or decrease the nominal stress amplitudes.

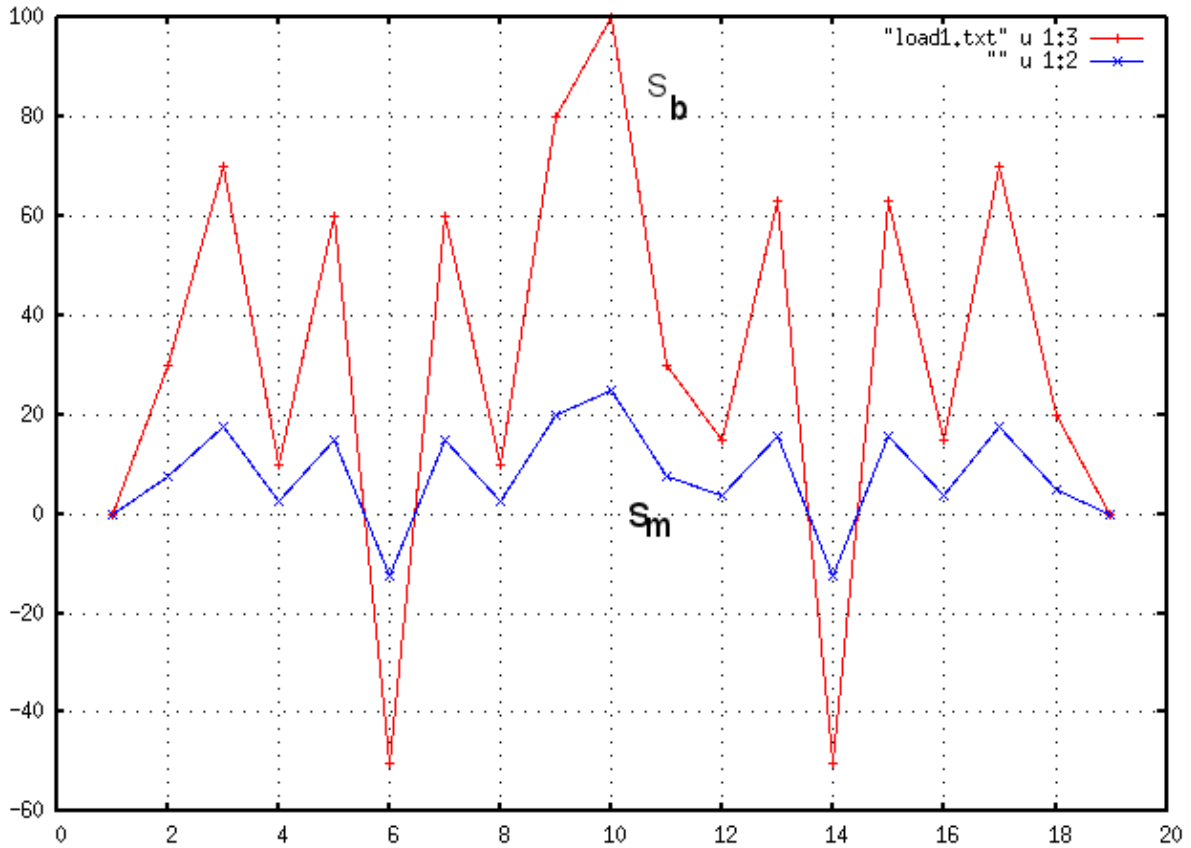


Fig. 2 :Load History used for simulation

The text form of the load history can be seen in the file

[load1.txt](#)

Each line of the file should contain a time number in first column, followed by a Membrane stress number and then a Bending stress number. Load history files can be defined in any scale e.g.: +-999 units. These are then scaled to stresses in the pdprop.env environment file described below or by inserting the appropriate multiplication factor at simulation run time. Generally the time variable is only used to edit the load file and is ignored during the actual crack propagation simulation.

(Note: if you wish to download the file be aware that it is a Linux type text file where the end of line character differs from those used in MS DOS text files. All text files linked to in this paper or of type Linux).

Crack Propagation Rate da/dn Computation

Crack propagation results from Newman[11], Haddad[12] and Klingerman[13] were combined into a single plot of da/dn versus Delta K (Crack increment per cycle vs. Stress Intensity Range). The data shown in the plot of Fig._3 are not the actual measured and reported points, but are manually digitized summaries of the reported data that show the trend and scatter. There appears to be little R (stress ratio) effect for these low carbon steels. A fitted curve (points interconnected by lines) was created from the plots is overlaid on the the

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original points is also shown in Fig. 3.

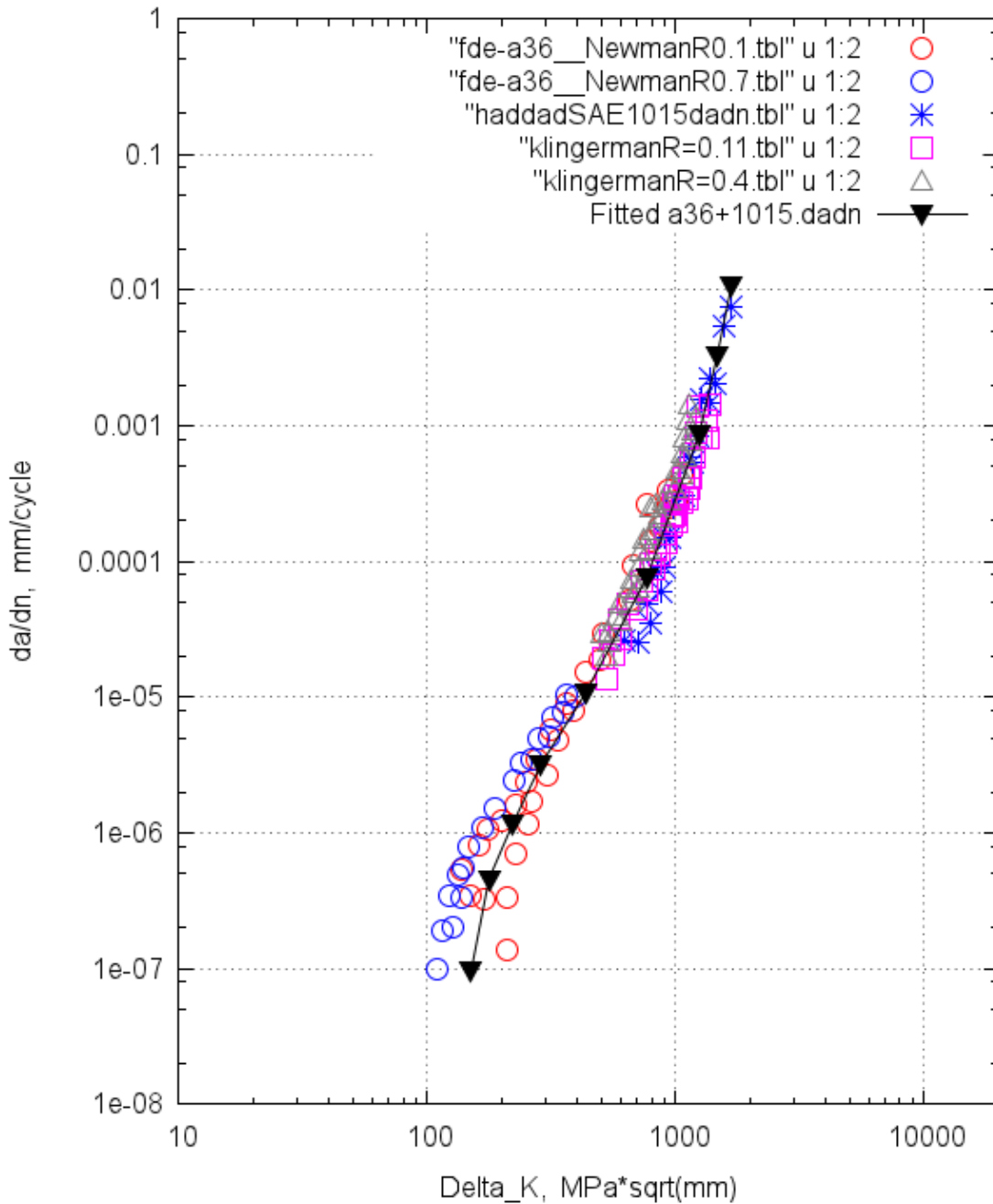


Fig. 3 :Plot of crack propagation rate versus Stress Intensity Range for A36 and SAE1015 steel with fitted data points overlaid.

The fitted points which were placed in a text file for the simulation are shown here:

```
#NAME= A36merged data from Newman, Haddad, Klingerman
#Data digitized from merged graph in file a36+1015dadn-c.png
#deltaKunits= mpa_mm
#dadnunits= mm
#
#MPa*sqrt (mm) dadn mm/cycle
```

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150.216	9.62054e-08
176.983	4.5623e-07
220.235	1.16017e-06
287.484	3.22409e-06
433.167	1.06976e-05
763.741	7.55681e-05
1240.59	0.000852041
1471.68	0.0033073
1675.69	0.0107468

The simulation programs read this dadn vs delta_K file and convert the points to logarithmic co-ordinate points along with a difference table of log(deltaK) increments to speed up simulation interpolation time.

Mm, Mb Factors for Plate Surface Flaw

Textbooks generally display the **Mm** and **Mb** stress intensity magnification factors in two dimensional form as shown in Fig. 4 for the 45 deg angle (the surface line is deemed as Zero degree). Typically the X axis is the variable a/B, and each curve is holds a/c constant.

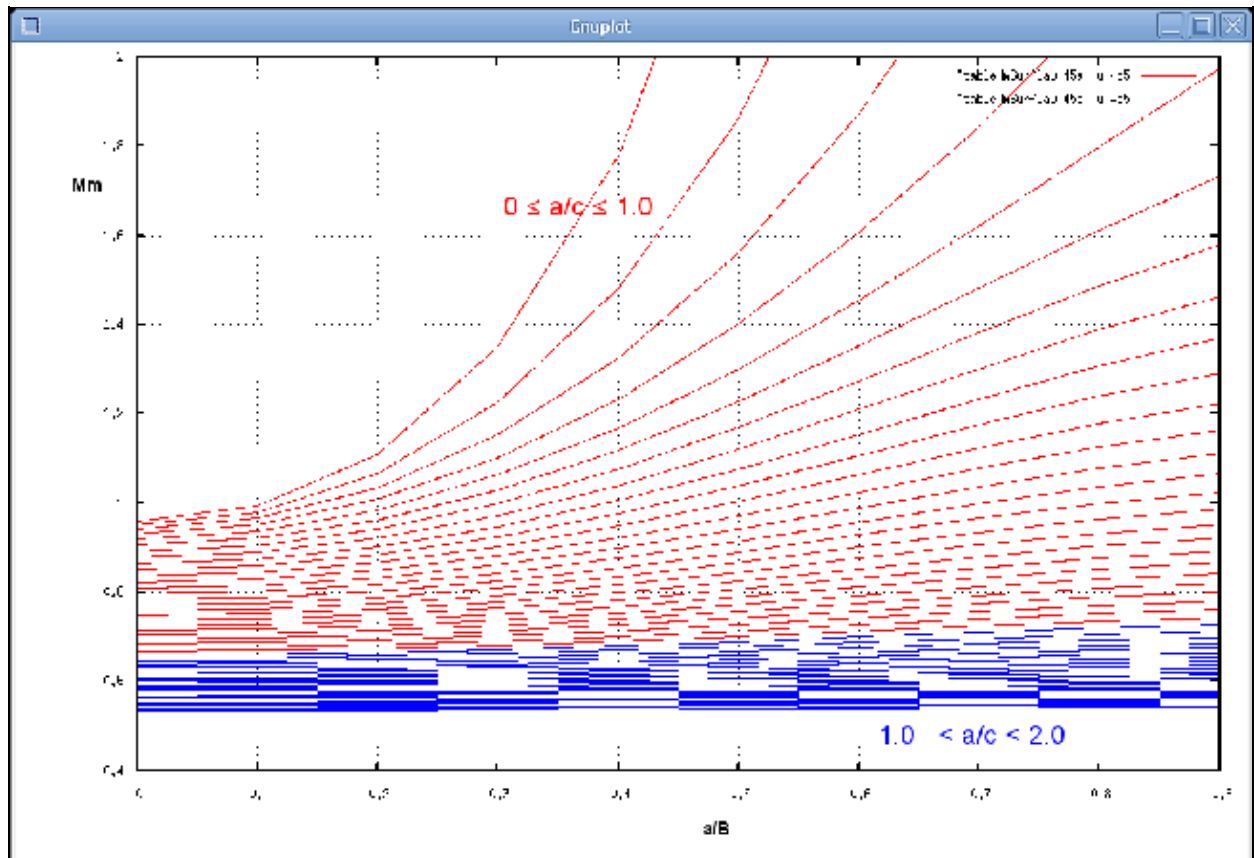


Fig. 4 :

This format is not efficient for the simulation however, and the data has been translated into a 2-D matrix of equally spaced a/B vs. a/c co-ordinates with the factor Mm and Mb values in the matrix locations. A matrix for each of Mm and Mb is transmitted to the simulation and the solutions for a given a/B and a/c value at runtime are computed using 2-D interpolation.

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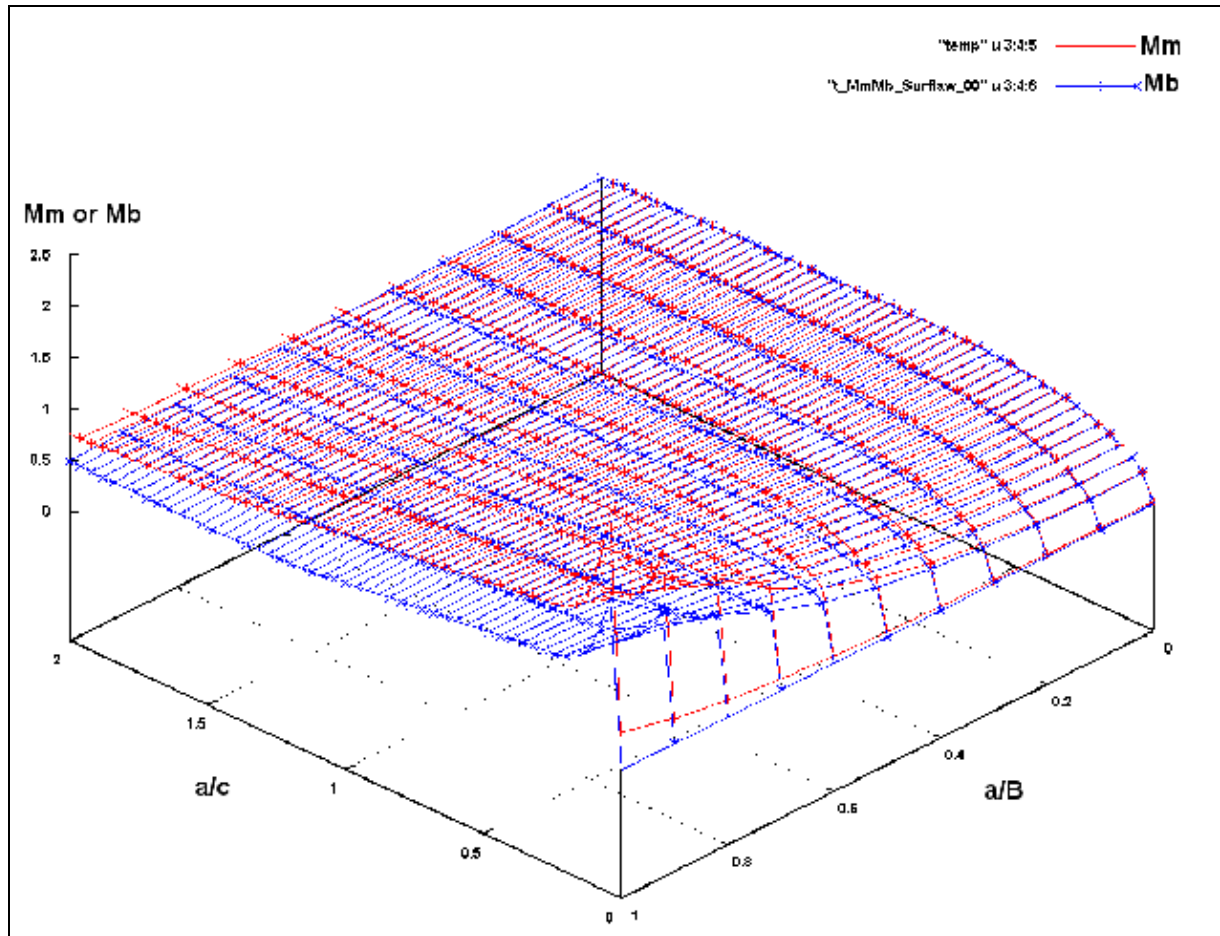


Fig. 5 :

Fig. 5 depicts both these surfaces in one plot for the 00 degree (where crack meets surface) location. Links to individual surface plots are provided in the following list:

- [Mb 00 deg.](#)
- [Mm 00 deg.](#)
- [Mb 90 deg.](#)
- [Mm 90 deg.](#)

Mkm, Mkb Factors for Plate Surface Flaw with Weld

A similar set of computations, storage, and interpolations are used in the simulation to compute the factors **Mkm** and **Mkb**. The factors in their matrix form for Mkb 00 deg. are displayed as a surface in Fig. 6 below while links to the other surface plots are listed below the figure.

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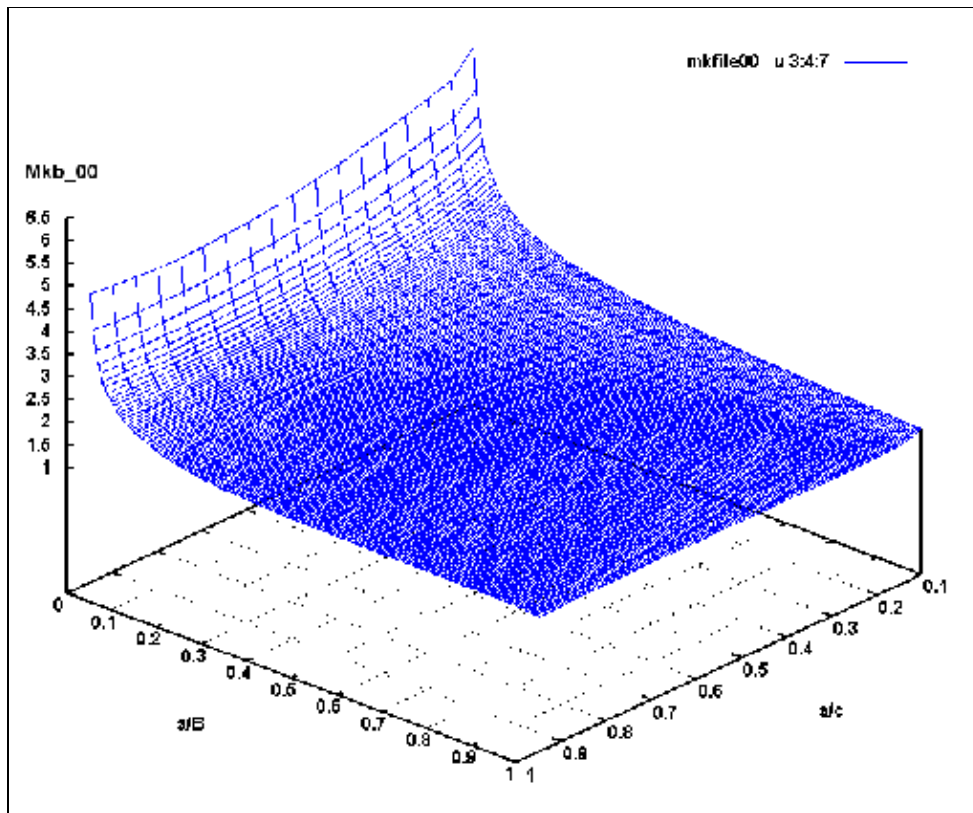


Fig. 6 :Mkb factor for bending, L/B= 1.0

- Mkm 00 deg. L/B= 1.0
- Mkb 90 deg. L/B= 1.0
- Mkm 90 deg. L/B= 1.0

Finite Width Correction factor: fw

The finite width correction factor fw is computed, stored and runtime interpolated in the same way as the above factors. The surface used for interpolation is shown in figure 7.

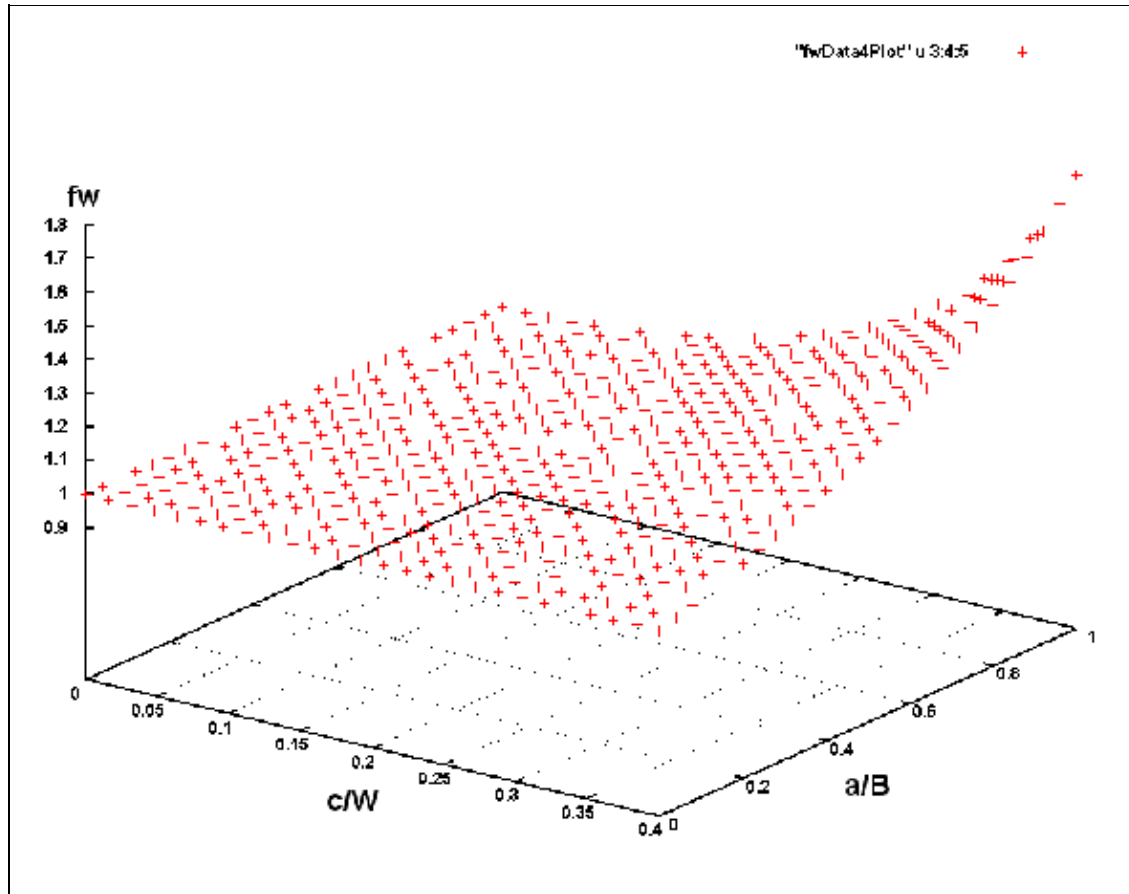


Fig. 7 :Finite width computation surface for surface crack in a plate.

The finite width correction factor fw is a function of a/B and c/W where W is the plate width.

Program Operation

The control file pdprop.env is read by both the initial setup script program and the simulation program itself. In this text file control commands or problem descriptors are defined by lines that start with **#tag= value** where the "#tag=" is some identifying string and value is a numeric value or character string descriptor. The pdprop.env file use for the simulations in this paper appears as:

```
# pdprop.env :      contains the starting filenames, variables etc
# for the Crack Propagation programs.  It should be edited by the
# user before each simulation type is run.
#
#TYPE= plate_surface_crack      #with or without weld using ACTIVATES below.
#                                #Other      #TYPE= options:
```

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```
#                                     # plate_wide_flaw (future code)
#                                     # plate_edge_flaw (future code)
#                                     # etc...
#ACTIVATE_MmMb= 1 # Deactivate = 0
#ACTIVATE_MkmMkb= 1
#ACTIVATE_fw= 1

# The factors described in this section may be ignored if not applicable to
# the particular problem type described above.
# (All dimensions in mm)
#B= 10.0 # plate (or pipe wall) thickness
#W= 70.0 # plate width
#ri= 0. # Internal diameter if pipe problem
#azero= 2.0 # initial crack depth
#czero= 4.0 # initial 1/2 crack width at surface
#L= 10. # Weld Feature width. Set to 0.0 if no Mkm or Mkb (weld)

#HISTORYFILE= load1.txt # historyFileName
# # Adjustments to load file variables:
# # Note that the MEANADD (below) is added AFTER the MAGFACTOR is applied.
#MAGFACTOR_m= 1.0 # Multiply factor on membrane load. Result should be MPa
#MAGFACTOR_b= 1.0 # Multiply factor on bending load term. Result should be MPa
#MEANADD_m= 0.0 # Mean shift in MPa added to membrane stress.
#MEANADD_b= 0.0 # Mean shift in MPa added to bending stress.

#MAXREPS= 1000000 # Max no. history repeats in simulation.
# # One repetition or application of the load history is
# # also called a "block" of cycles.
#
#
#MATERIAL= merged_a36_fitted.html #File name of material fitted data
# This file is used to define the cyclic
# stress-strain curve, and the Neuber Product curve.
#
#DADN= table # Can be "table" or "Paris"
#DADN_PARIS= 0.0 0.0 0.0 0.0 none # Kth a m Kc units (ignored if #DADN= table )
# !! units specify: mpa_m or ksi_in or mpa_mm
#
#DADN_TABLE= a36+1015.dadn # da/dN digitized da/dN curve for material,
# including the threshold, and K1c.
# If a threshold exists, put in a vertical line
# (with two identical X-axis points).
# If the threshold needs to be "turned off" then
# do NOT put in a vertical line at low da/dN.
# (Ignored when #DADN= PARIS )

#FAD Stuff:
#TensileFile= a36_Mattos_mono_engrSS_FLAT.txt #enter "none" if no FAD
#PmEOL= 70. #Set these so that Pm+Pb= 0.82*Syield for default.
#PbEOL= 100.
#Kmat= 1675.
#PinJoint= 0 #Set = 1 if struture is pinJointed (for bending)
#
#
#BLOCKSKIP= 1.0 percent # At the end of each block check if the previous
# two blocks of cycles had similar damage (crack
# extension) within this percentage. If TRUE then
# simply skip the simulation of the next block,
# but just add the expected damage. Continue by
# simulating the block after the skip.
# A value of 0.0 will disallow skipping blocks.
#SAVELEVEL= 0 #Amount of output saved to disk: ( 0 is normal)
```

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```
#           #   3=lots  2=medium  1=minimal
#           #   0= save #crk=  data into binary direct access file only
#           #       No #crk=  data will be written into the text logfile.
#           #       Use for large output files with lots of cycles.
```

Lines in the above file that begin with a # but are not "tags" are simply treated as comments and ignored in the simulation.

After the control script, or the user manually, has set up the various input files, the simulation is commenced with a command such as:

```
./plateWeldflaw  scaleFactor < loadHistory > outputFile
```

where scaleFactor is an additional multiplier activated after the multipliers and mean shift tags found in the pdprop.env file have been applied. This allows the user to run several problem sets with the same pdprop.env conditions but scaled to different magnitudes without editing the pdprop.env file. e.g.:

```
./plateWeldflaw  0.95 < load1.txt > result0.95.txt
./plateWeldflaw  0.90 < load1.txt > result0.90.txt
etc...
```

It is possible that the user may have inserted a non-reversal into the load history by accident or due to the effects of the magnification and mean shift factors. Because the simulation code presently requires that each point of the load history be an actual reversal point (change in direction of loading), the history is scanned with the aim of eliminating the non-reversal points. The criterion for this scan is the total Stress = $P_m + P_b$. The resulting corrected load file is also written out for use by a traditional stress-strain-life initiation fatigue program. It is prudent however for the user to plot the corrected stress history file to see if it still meets her/his expectations.

After the initialization phase has been completed the simulation begins to run each half-cycle of the history file. The Push-Down list (or Last-In-First-Out) material memory code is activated separately for each of the 00 degree crack direction and the 90 degree crack direction; effectively two separate pieces of code that run with their own list storage. This is necessary because the counting process is done on the stress intensity K_{max} and K_{min} values after the application of the various M_m , M_b , f_w , etc factors to the membrane and bending stresses. At the end of each 1/2 cycle the values for crack length a and c are updated with the projected crack increments. The next 1/2 cycle is then processed with the updated a and c values.

An additional code feature is that the K_{max} and K_{min} values are discretized into between 1000 and 2000 equal spaced values. This was found to be advantageous in reducing the size of the material memory Push-Down list. Without discretization as the crack propagates out of the influence zone of the weld or notch, each load block's largest K_{max} value will be slightly less than the previous load history block's K_{max} value. This results in tens of thousands of entries in the Push-Down list, which, although doable with modern memory sizes, is wasteful and not really necessary. A discretization of K_{max} and K_{min} with only a loss of accuracy of about 1 per 1000 is an acceptable compromise to help limit program size.

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All initial data and each 1/2 cycle's information is written to files. After the program completes, generally when one of the Mm, Mb, fw or other factor constraints have been exceeded, the output text file can be quickly scanned for individual bits of information. Tags similar to those used in the pdprop.env file are detected to allow the post processing routines to extract only the information that they need to produce each graph and summary statistic. For the output report the large individual 1/2 cycle file is scanned for max/min for each parameter and condensed into 1000 summary points for the creation of graphs and other report data.

It should be noted that in this program version no allowance is made for the effect of a propagating crack on the material memory (Push-Down list) settings. Simulation features such as plastic zone size, prior crack length, etc. could be easily stacked in the same Push-Down list scheme and used to influence damage computations.

Simulation Results using Material Memory

Figures 9 and 10 depict the history of the Kmax and Kmin variables during the simulation. The history file of figure 2 was simulated after a magnification factor of 0.95 was applied to the stress values.

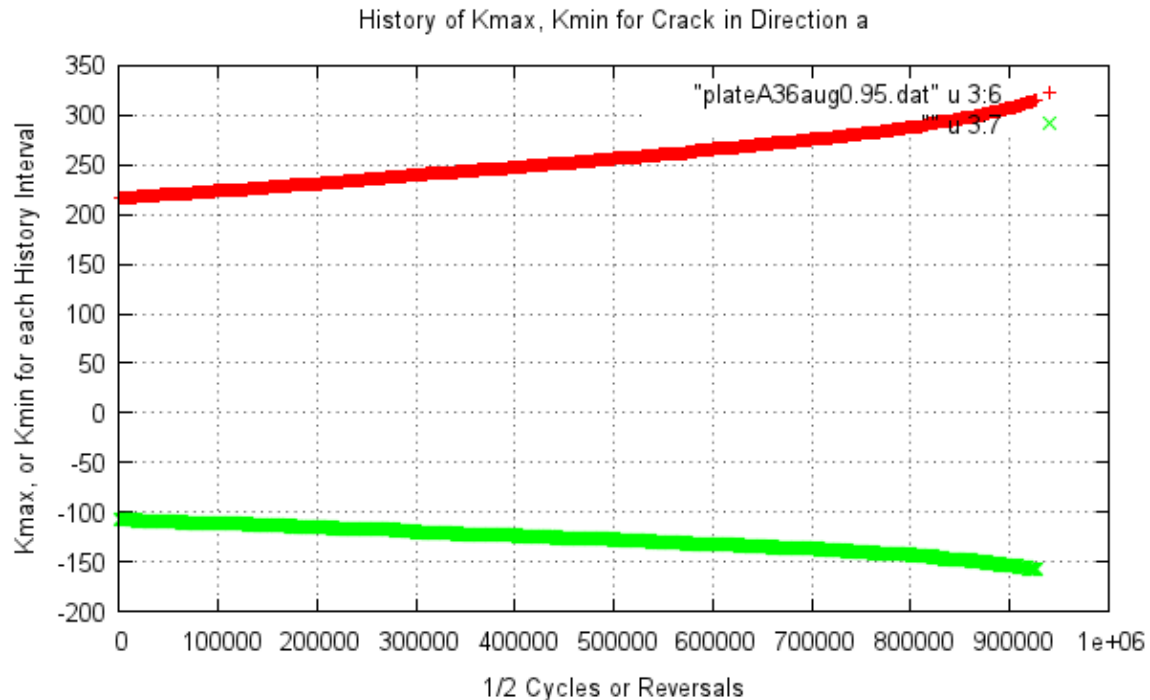


Fig. 8 :History of Kmax and Kmin using Material Memory for 90 deg. simulation.

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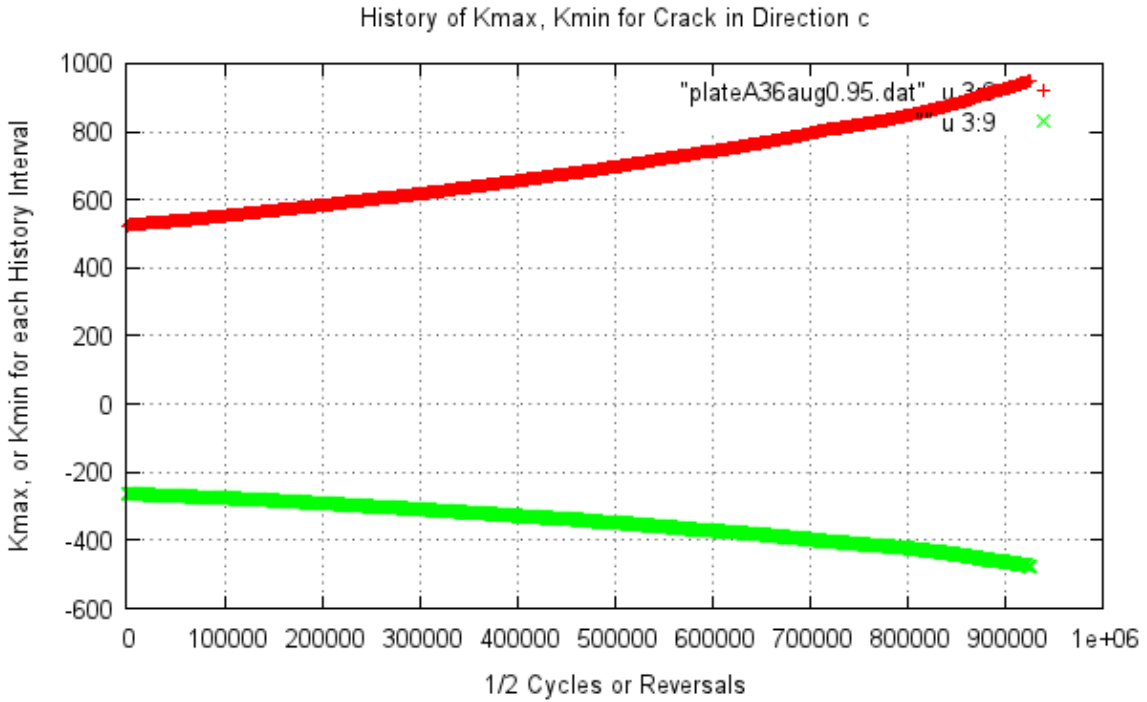


Fig. 9 :History of Kmax and Kmin using Material Memory for 00 deg. simulation.

The same result is reflected in the plot of the crack propagation history of both crack length **a** and crack length **c**. The simulation was ended when the value of **a/c** reached the computational boundaries defined by the equations for the various multiplication factors. Simulation time for this test was about 0.3 seconds using a 2009 era desktop cpu without activation of multi-threading.

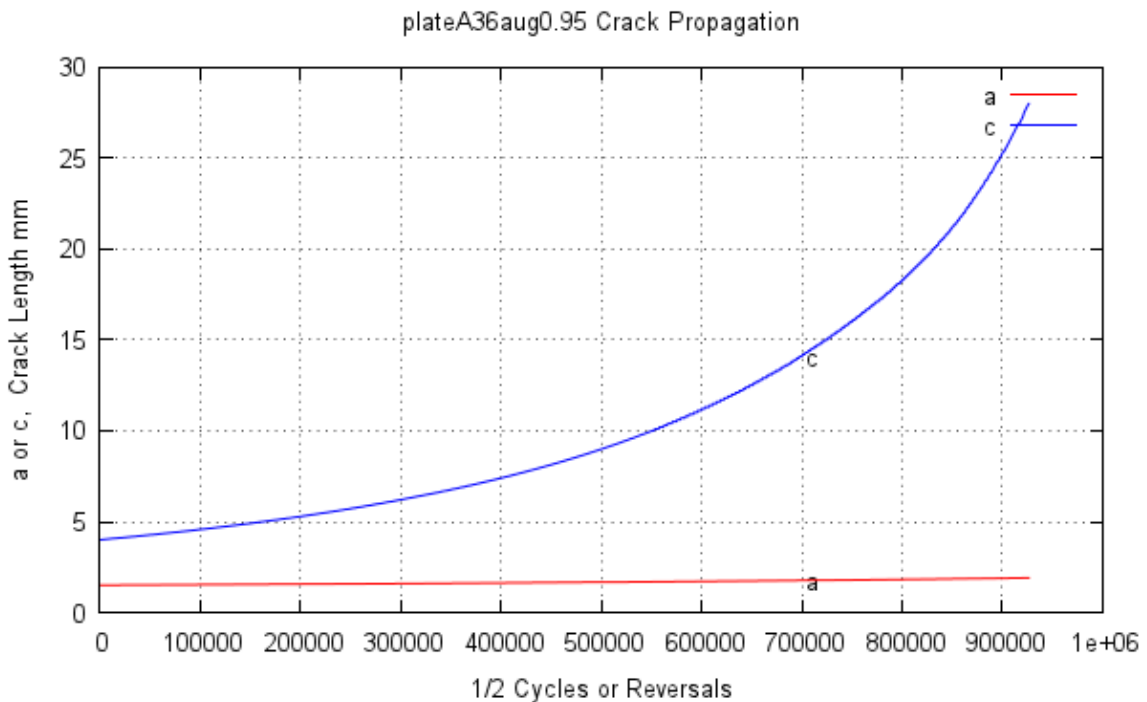


Fig. 10 :Simulation of the change in **a** and **c** when subjected

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to the test history with magnification factor 0.95.

From the results file one can also plot the paths of various magnification factors in terms of the crack length variables. Figure 11 shows such a plot for the various factor.

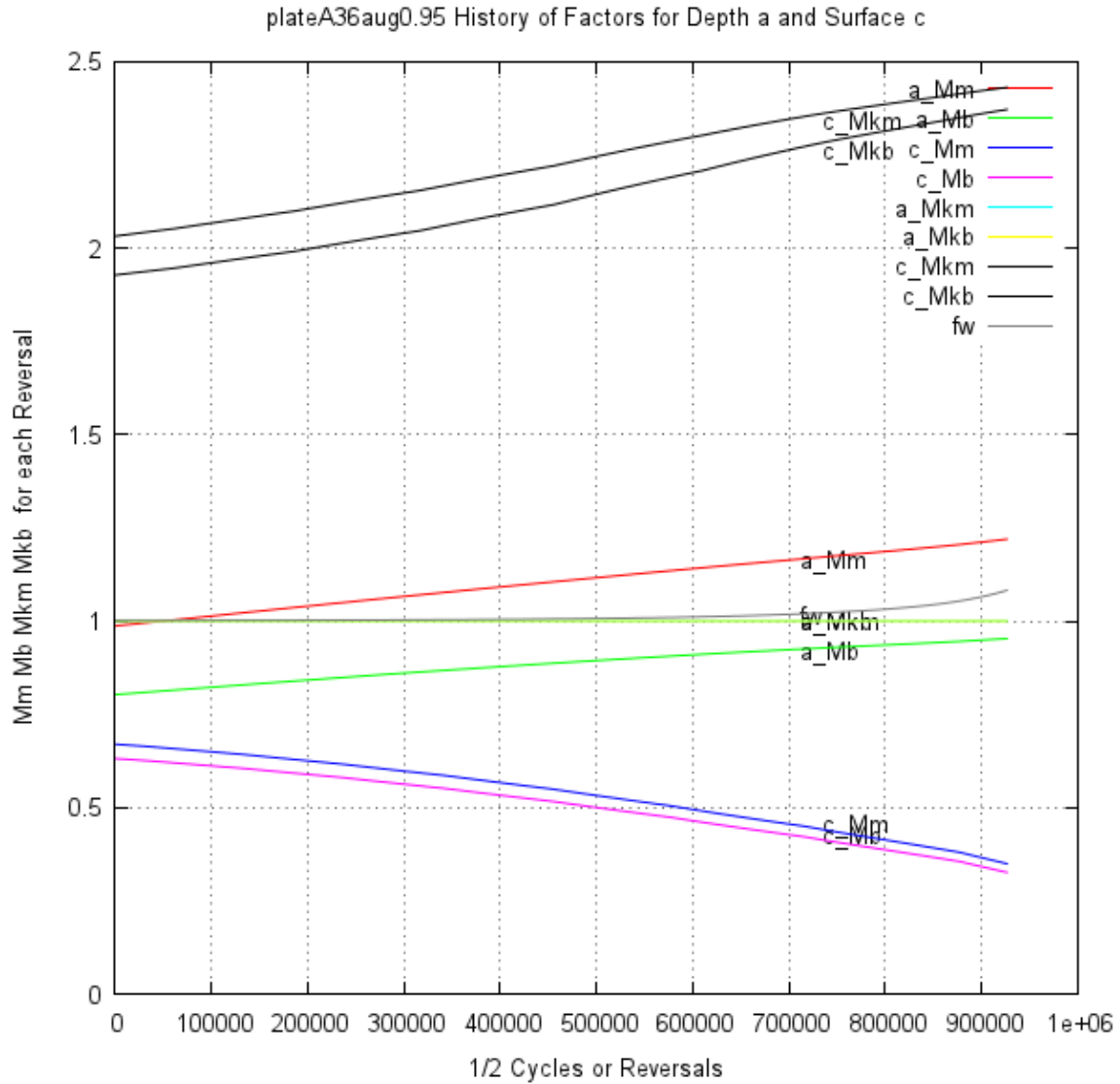


Fig. 11 :Plot of various multiplication factors during simulation.

When tensile test stress-strain curve is available the output data can also be used to construct a FAD (Failure Analysis Diagram). Figure 12 depicts the ratio of the applied fracture conditions to final fracture conditions on the Y axis and the ratio of the applied load to that required to cause plastic collapse.

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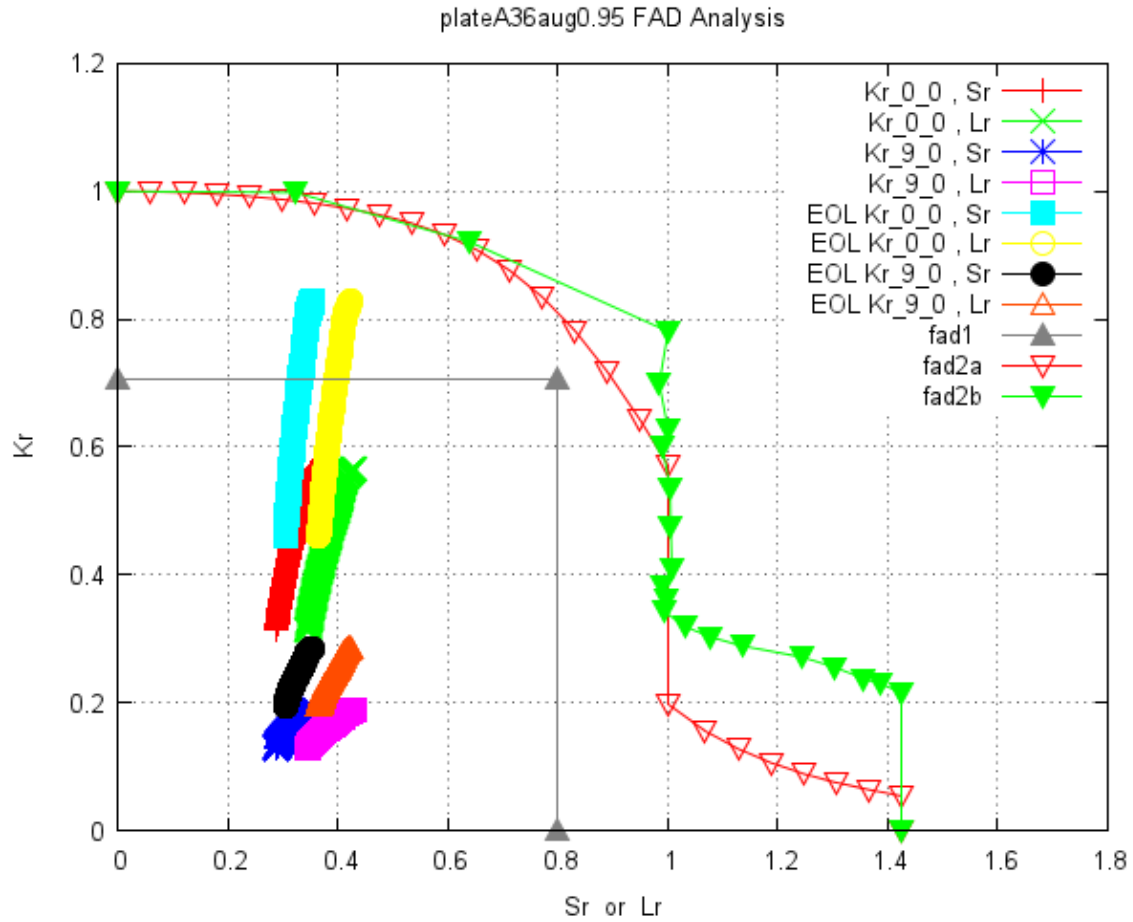


Fig. 12 :Failure Analysis Diagram plot for simulation with FAD limits defined by A36 steel tensile test results.

The plotted points on the graph show the outline of the limiting field (inside is ok) and the worst case FAD ratios for each of the 1000 cycle intervals of the test.

Prediction Results based on Simple Range Count

In the computer simulation code it is a fairly easy process to turn off the material memory counting process by removing some lines of code in the program. When Kmax and Kmin are then computed from successive points in the history only, without regard to any cycle counting adjustments, one obtains a "Simple Range Count" simulation. The results of such a simplification, shown in figure 13, are contrasted with the earlier Push-Down list results described above.

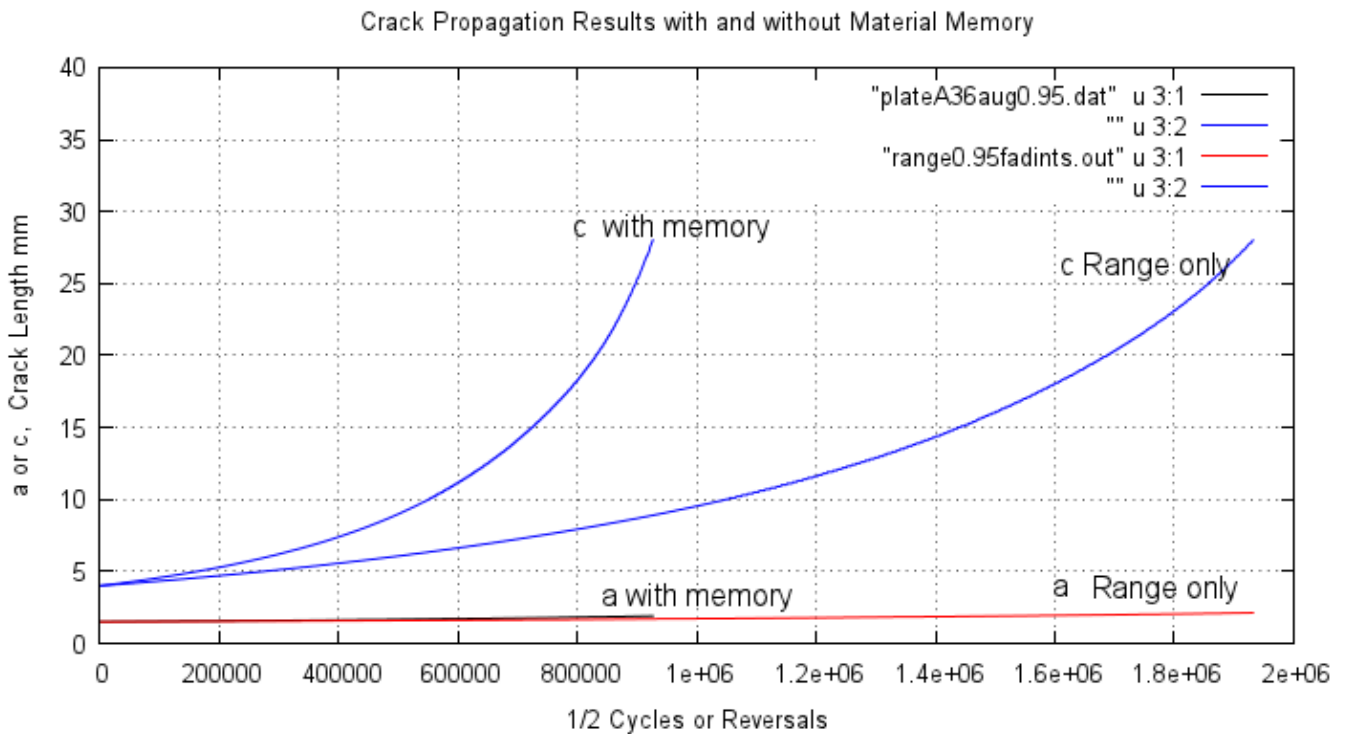


Fig. 13 : Simulation of the change in **a** and **c** using material memory cycle counting and simple range counting.

The difference in Range count vs. Memory count simulation life, as indicated by the value of **c**, is a ratio of 1.7. Similarly at a lower level of load history multiplication factor of 0.70, the ratio of 2.1.

From the results one can conclude that crack propagation simulations using simple range counting approximately double the propagation life. A study is presently underway to compare both methods to actual variable amplitude test results documented in the literature.

Summary:

The incorporation of an accounting method to simulate the effects of material memory, which is of critical importance in crack initiation simulations, has been shown to be easily adaptable to crack propagation simulations. Simple Range counting to determine cyclic damaging events can lead to serious underestimation of the damage cause by large overall cycles that are interrupted by smaller cycles during the completion of the larger half-cycles. A factor of two on the non-conservative side was observed using the fairly simple history

of this study.

Based on the experience and research in counting damage for crack initiation assessments it is expected that an allowance for material memory events during the resolution of damaging events is also important in any crack propagation simulation.

Further studies are underway to simulate crack propagation in specimens and components subjected to a variety of variable amplitude histories.

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