AN EVALUATION OF SERVICE LIFE ANALYSIS OF METALLIC AIRFRAME STRUCTURE WITH MSC/FATIGUE

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ABSTRACT

Initial demonstrations of MSC/FATIGUE, a comprehensive finite-element based durability analysis software system, have generated interest because of the potential for its use to benefit the preliminary design of airframe structure. An evaluation of the software was performed in order to determine its suitability for application to this preliminary design environment, and this paper summarizes the evaluation task. The primary evaluation consisted of comparing fatigue crack initiation predictions of MSC/FATIGUE with results from another analytical method, coupon test data, and component test data. Several positive conclusions resulted from this evaluation of MSC/FATIGUE: 1) the crack initiation capabilities of MSC/FATIGUE are state-of-the-art with regard to both advanced CAE/visualization and current fatigue crack initiation theory, 2) fatigue crack initiation predictions compare favorably with those generated using another analytical technique as well as with test data, 3) MSC/FATIGUE is useful for detailed analysis, and 4) MSC/FATIGUE is a candidate tool for durability assessment during preliminary design. The primary advantage of MSC/FATIGUE was discovered to be its ability to locate areas in a structure that may be susceptible to crack initiation.

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INTRODUCTION

MSC/FATIGUE[1], developed jointly by The MacNeal-Schwendler Corporation and nCode International Limited, is a comprehensive finite-element based durability analysis software system. Initial demonstrations of this product generated interest because of the potential for its use to benefit the preliminary design of airframe structure. The software could allow circumvention of future life-limiting problems that might result from design without sufficient consideration of fatigue issues. An evaluation of MSC/FATIGUE was performed in order to determine the suitability of the software for application to this preliminary design environment, and this paper summarizes the work completed during this evaluation task.

Three types of durability analyses can be conducted with MSC/FATIGUE: total life, crack initiation, and crack growth. Preliminary demonstration of the software's crack growth capabilities suggested far less maturity than the advanced capabilities dealing with analysis of fatigue crack initiation. Because of this, and the fact that the potential for improving preliminary design would result primarily from the application of initiation analysis methods to structural design, this evaluation considered only the fatigue crack initiation capabilities of the software.

PRELIMINARY MSC/FATIGUE EVALUATION

The evaluation of MSC/FATIGUE was comprised of three types of comparisons. First, results of MSC/FATIGUE were compared with results generated from another analytical method, results were next compared with coupon test data, and finally, results were compared with test data obtained from a structural component test.

Comparison of MSC/FATIGUE with LOOPIN

The following three examples summarize the results of comparing MSC/FATIGUE with an in-house version of LOOPIN[2] (LOOPIN is a closed loop fatigue crack initiation computer program that was developed by Northrop – the version used was a highly modified in-house version of this Northrop code). In order to evaluate a range of MSC/FATIGUE capabilities, each example is slightly more complex than its predecessor.

<u>1. Model of a smooth unnotched bar specimen</u>
A model of a small round-bar tension specimen was generated using MSC/PATRAN[3] and this model was analyzed with MSC/NASTRAN[4]. Results of the analysis, combined with necessary materials information and loading histories, were the starting point for analyses with MSC/FATIGUE. Three different materials were considered: one steel (4340), one aluminum (2024-T851), and one titanium (Ti-6Al-4V MA). Two spectra were studied: a simple fully-reversed sinusoidal waveform and a more complex FALSTAFF[5] spectrum corresponding to a typical fighter aircraft loading history. Results of the constant amplitude analyses are presented in Fig. 1, and are quite encouraging as the MSC/FATIGUE results agree with the LOOPIN results over the entire range of

applied stress. The variable amplitude results (Fig. 2) do not agree with one another quite as well as the constant amplitude results do, but are still very good.

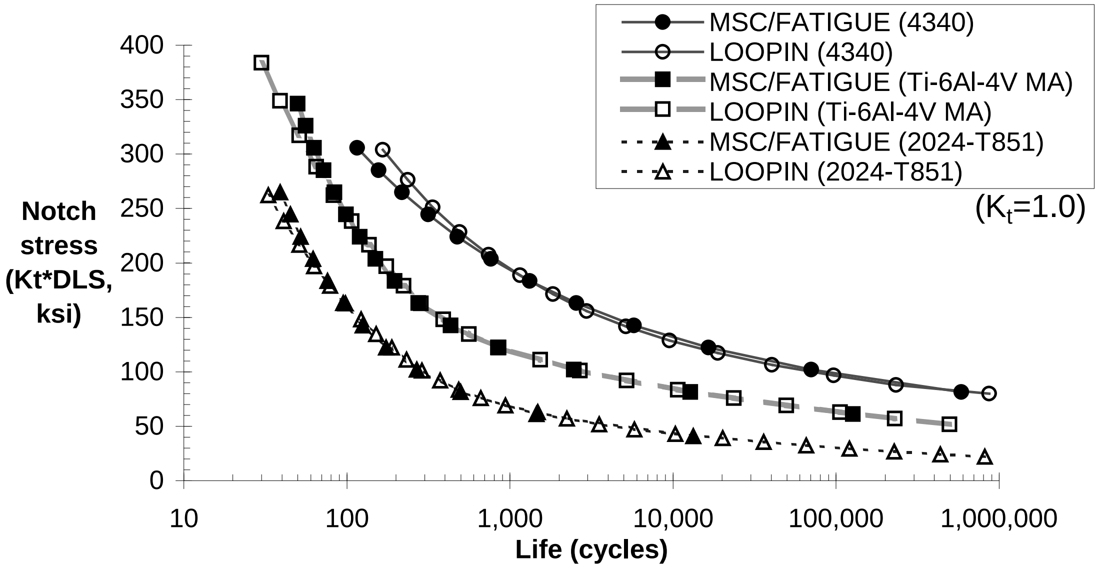


Figure 1. MSC/FATIGUE and LOOPIN results - smooth specimen, constant amplitude

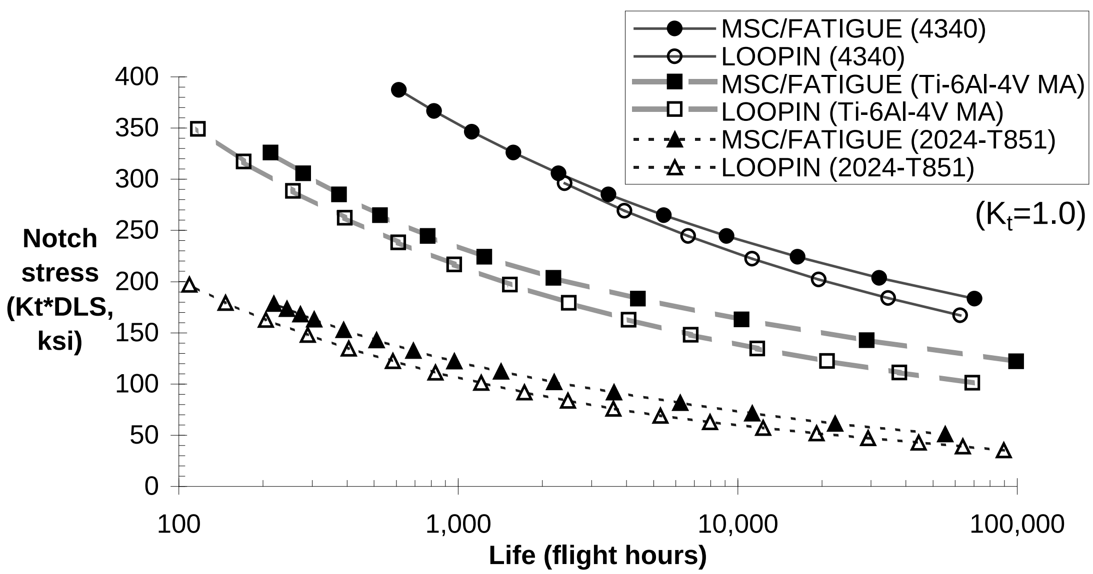


Figure 2. MSC/FATIGUE and LOOPIN results - smooth specimen, FALSTAFF

<u>2. Model of a hole in a finite width strip</u>

A two-dimensional model of a simple dogbone specimen with a hole in the center was analyzed because it allowed a stress concentration to be included in a very simple geometry. Note that when using LOOPIN, the user must explicitly define the stress concentration factor (K_t) at the edge of the hole, and therefore the initiation location must be known before the analysis is attempted. With MSC/FATIGUE, on the other hand, the K_t value is determined implicitly from the finite element results. (This could be important if, for example, the notch stresses at the radius between the grip section and the gage section were larger than at the hole – MSC/FATIGUE would warn of the potential danger while LOOPIN would not). Figures 3 and 4 present comparisons of MSC/FATIGUE and LOOPIN for analyses of the model subjected to the constant amplitude and the FALSTAFF loading histories, respectively (each method included all three materials). The results behaved in a very similar manner as did those from the first example, and this is encouraging because the slight increase in model complexity should not produce noticeably different answers.

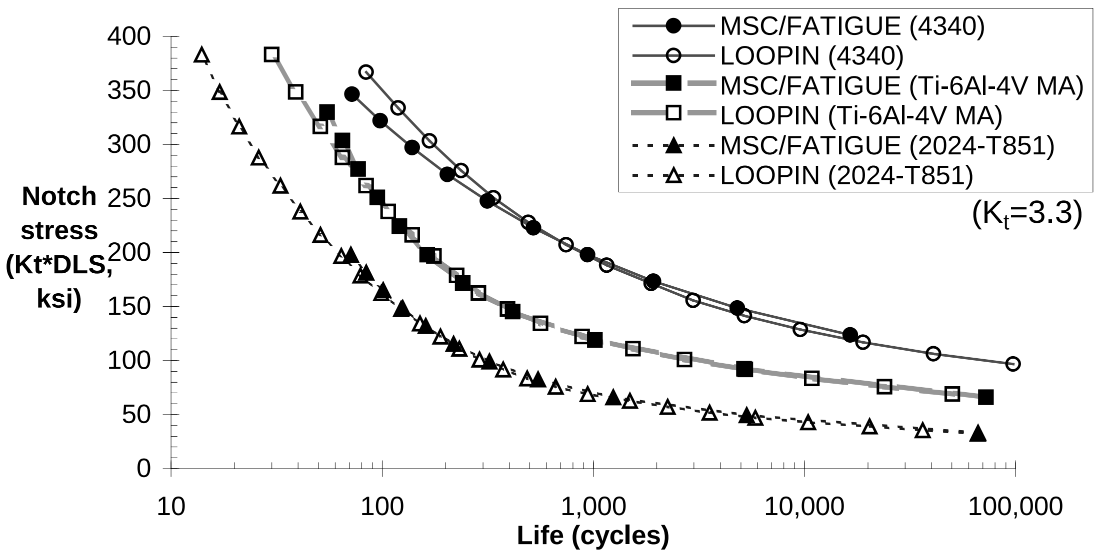


Figure 3. MSC/FATIGUE and LOOPIN results - hole specimen, constant amplitude

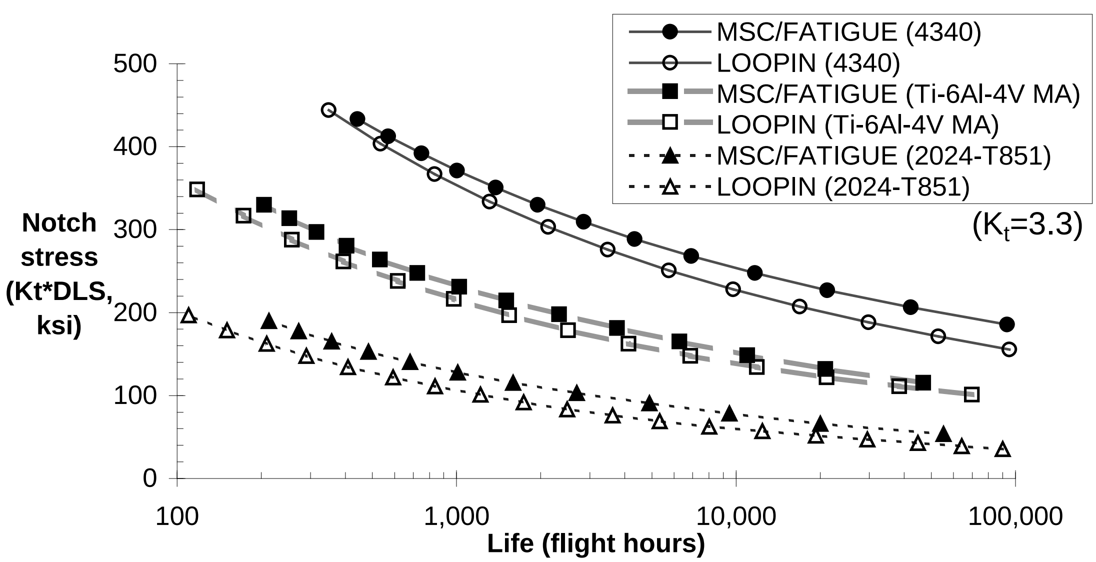
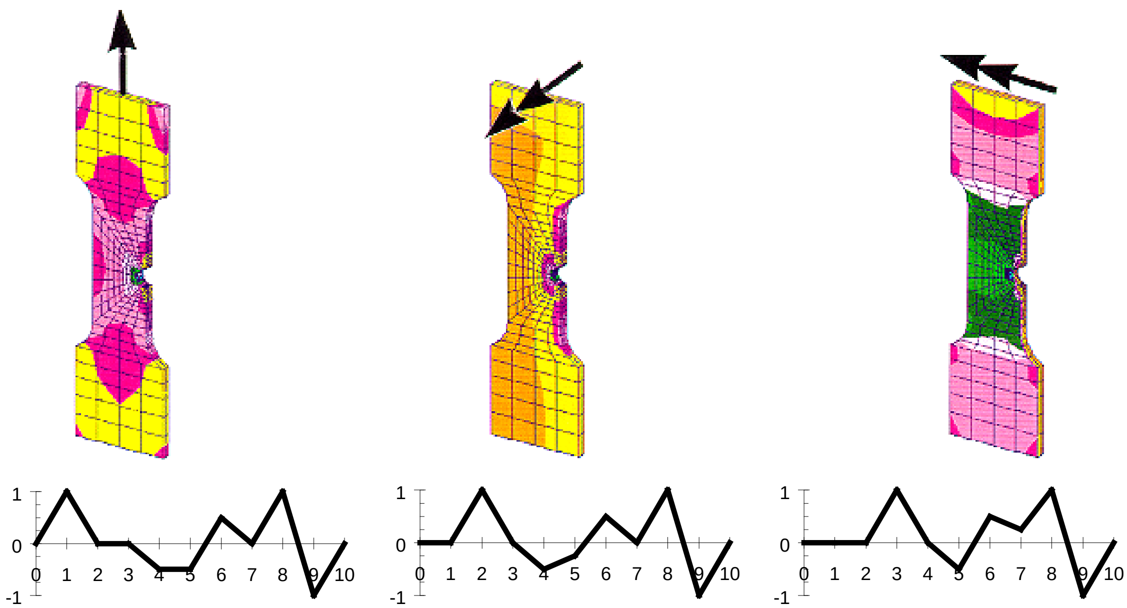


Figure 4. MSC/FATIGUE and LOOPIN results - hole specimen, FALSTAFF

3. Model of combined loading of a notched dogbone specimen

The third comparative example expanded upon the previous examples by considering three independent loads applied by way of three independent load histories (see Fig. 5 for the finite element model loading descriptions and respective spectra). Finite element results corresponding to an axial force, an in-plane bending moment, and a transverse bending moment were generated by modeling a semi-circular edge notch geometry with MSC/PATRAN and analyzing the model with MSC/NASTRAN. These results, along with the independent load histories presented in Fig. 5, were used in an MSC/FATIGUE analysis. The resulting predictions compare favorably with LOOPIN (Fig. 6).

This example could be considered somewhat analogous to a potential future ability where a finite element model of an entire airframe could be analyzed with MSC/FATIGUE. Loading on the wings, the vertical tail, the horizontal tail, and so forth could be applied by way of independent loading histories in order to explicitly define the flight of a specific aircraft.



(a) axial force (b) in-plane moment (c) transverse moment

Figure 5. Finite element models (with results) and corresponding loading histories for combined loading of three-dimensional semi-circular edge notch geometry

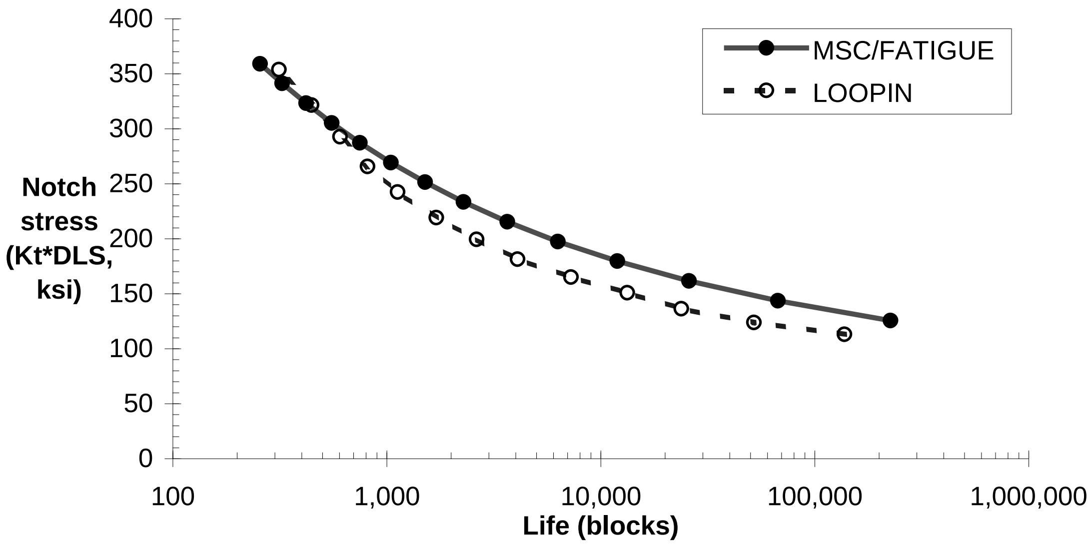


Figure 6. MSC/FATIGUE and LOOPIN results - combined loading example

Comparison of MSC/FATIGUE with coupon test data

The first three models analyzed during the MSC/FATIGUE evaluation involved simple examples that were used in order to compare results with another analytical method. It was also desirable to compare predictions using the software with actual test data. Four additional MSC/FATIGUE analyses were attempted in order to accomplish this goal.

<u>1. Purdue University/ALCOA crack initiation study</u>[6]
A study of fatigue crack initiation in 7050-T7451 aluminum plate was conducted by Purdue University, and very accurate initiation data (for life to a 0.01 inch crack) were obtained by use of the replication method. The material, produced by ALCOA, was provided in three material pedigrees which corresponded to improving resistance to initiation as a result of fewer inclusions and pores within the microstructure of the material. A simple double edge notch geometry (with semi-circular notches) was subjected to a constant amplitude load history at a stress ratio of 0.1 and four levels of maximum applied stress.

Results of the analysis are presented in Fig. 7. Note the spread of the test data, with the more susceptible material generally to the left of the scatter group and the more resistant material generally to the right. Results of the MSC/FATIGUE analysis appear to agree relatively well with both the test data and with the LOOPIN prediction. The results are on the unconservative side of the test data, however. Additional analyses might attempt to improve the MSC/FATIGUE results by providing strain-life data for each material pedigree, a refined mesh around the notch, or use of any number of other options – this exhibits that the user has several available choices when using MSC/FATIGUE.

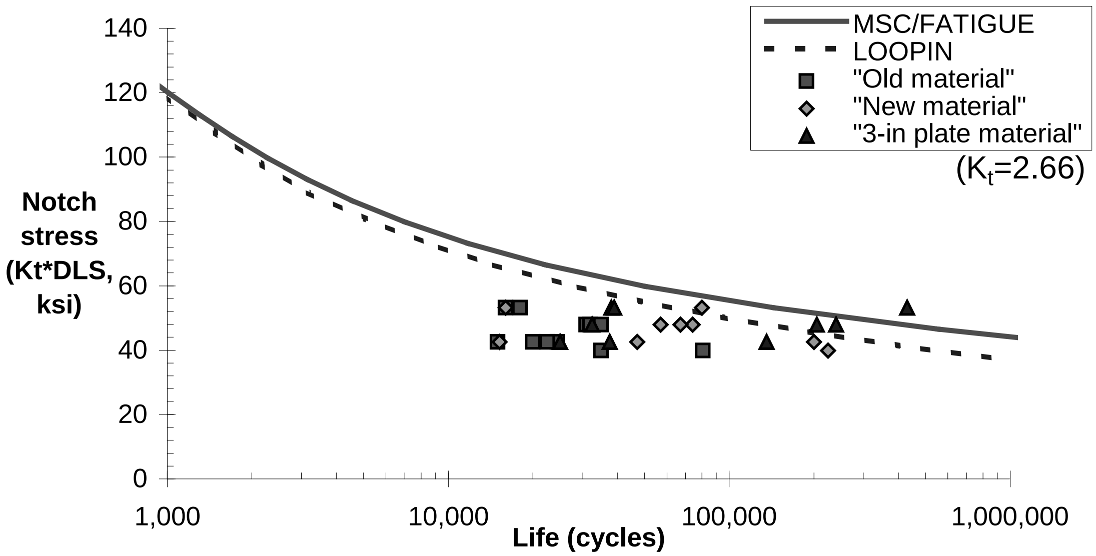


Figure 7. MSC/FATIGUE, LOOPIN, and test results - Purdue/ALCOA specimen[6]

2. Blunt edge notch geometry

Test data corresponding to a second double edge notch geometry were obtained from another source[7]. This data corresponded to the fully reversed loading of specimens manufactured from a medium strength steel. Various levels of maximum load were applied. Results of the MSC/FATIGUE analysis of this example are presented in Fig. 8 along with LOOPIN estimates. The MSC/FATIGUE results appear to be superior to the LOOPIN results for this situation. Neither method appears to accurately predict the initiation life for the test at the maximum stress level, but MSC/FATIGUE compares favorably to the test data over the remaining applied stress range. The lack of agreement at the higher stress may not be a shortcoming of either analytical method, but could in fact be due to inadequate strain-life data for the material involved. This emphasizes the need for proper data, no matter which analysis method is used.

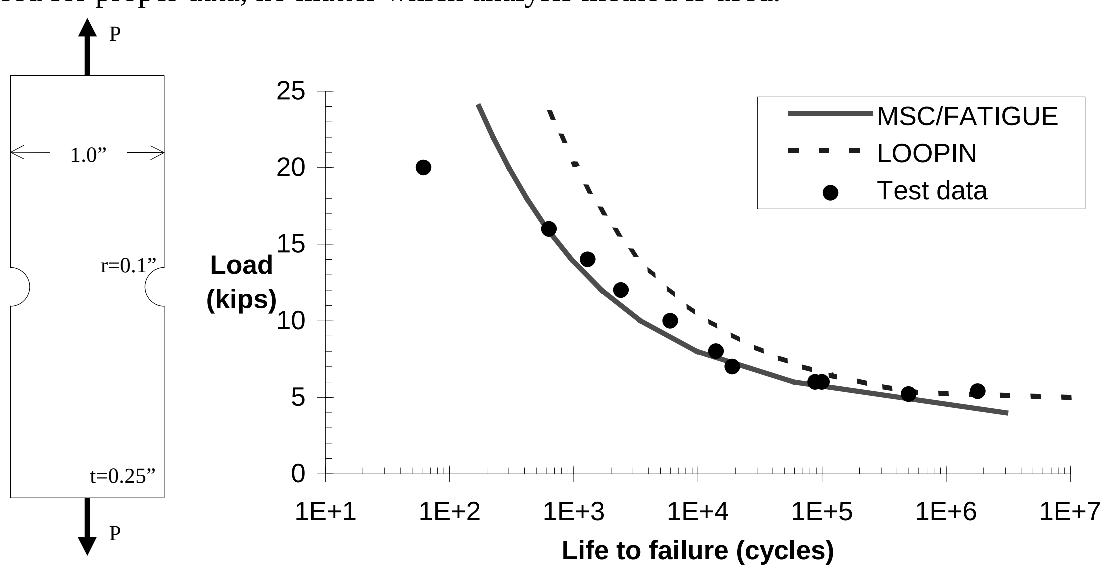


Figure 8. MSC/FATIGUE, LOOPIN, and test results - blunt edge notch specimen[7]

3. Center hole geometry

The reference that reported the previous test data also contained test data corresponding to a center hole geometry[7] (this specimen was made of the same material and was tested in a similar manner as was the previous specimen). Results of this analysis (Fig. 9) again reveal that good results were obtained from MSC/FATIGUE. As was the case with the previous example, MSC/FATIGUE was better able to predict the initiation lives for tests at the lower stress levels than at the higher stress levels, but this again may be a result of the quality of the material data reported.

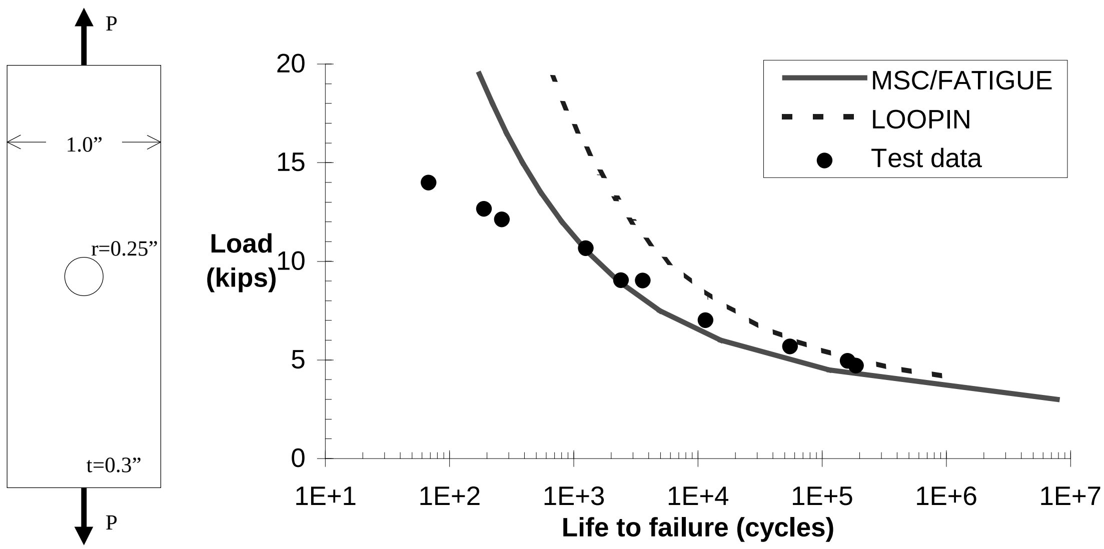
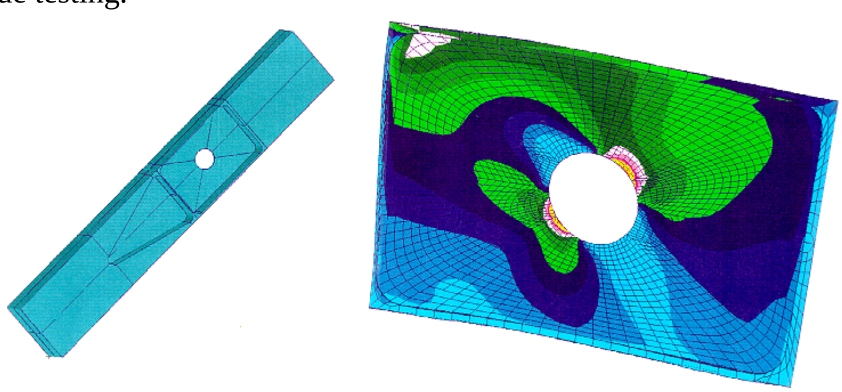


Figure 9. MSC/FATIGUE, LOOPIN, and test results - center hole specimen[7]

4. Shear web beam

Various shear web beams were tested for an advanced fighter aircraft program, one of which was modeled with MSC/PATRAN and analyzed with MSC/NASTRAN and MSC/FATIGUE. A solid model geometry of the test specimen is presented in Fig. 10 along with finite element results near the hole region (the maximum principal stress is shown on a deformed mesh). Finite element analysis revealed areas of high stress at the upper-right and lower-left areas of the circular hole, and this is where cracking occurred during fatigue testing.



(a) solid model (b) FEA results (hole region)

Figure 10. Shear web beam specimen

Analysis of this model with both MSC/FATIGUE and LOOPIN resulted in the sensitivity analyses presented in Fig. 11. Note that because the maximum stress at the hole edges was not located such that cracking would be expected to occur normal to either the longitudinal or long transverse grain directions, the model was analyzed multiple times. The first case assumed longitudinal material properties and the second case assumed long transverse properties. In addition, it was unknown whether or not the load history used during this analysis was the exact spectrum applied to the specimen during testing. The load history used during the analysis, if it was in fact different, was believed to at least be representative of the test spectrum because of similar statistics (i.e., the number of load points, the time and relative size of the maximum stress, the time and relative size of the minimum stress, and the total block time were very similar in both histories). Results of the MSC/FATIGUE analysis were quite encouraging, although once again the MSC/FATIGUE results were less conservative (or more unconservative, relative to the test data point) than the LOOPIN results.

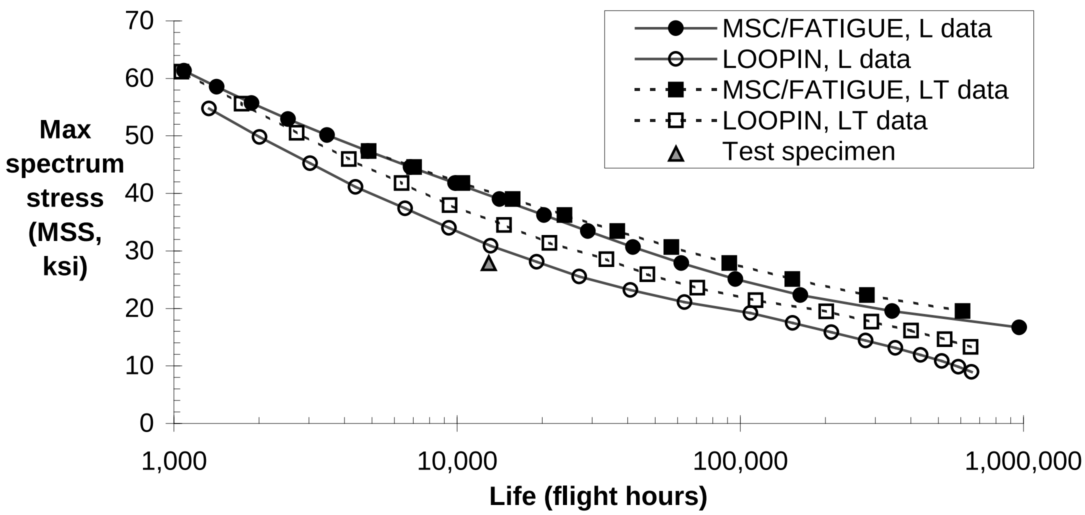


Figure 11. MSC/FATIGUE and test results - Shear web beam

Comparison of MSC/FATIGUE with component test data

The previous comparisons were all based upon very simple geometries, but it was also desired to analyze a much more complicated scenario using MSC/FATIGUE. The F-16 479 bulkhead test component[8] was chosen for this purpose. A post-failure photograph of one of these test components (Fig. 12) indicates the location of fatigue crack initiation at the radius between the bulkhead and one of the two vertical tail attach pads. It was expected that MSC/FATIGUE should be able to predict both the location of cracking and the rapid initiation of these cracks.

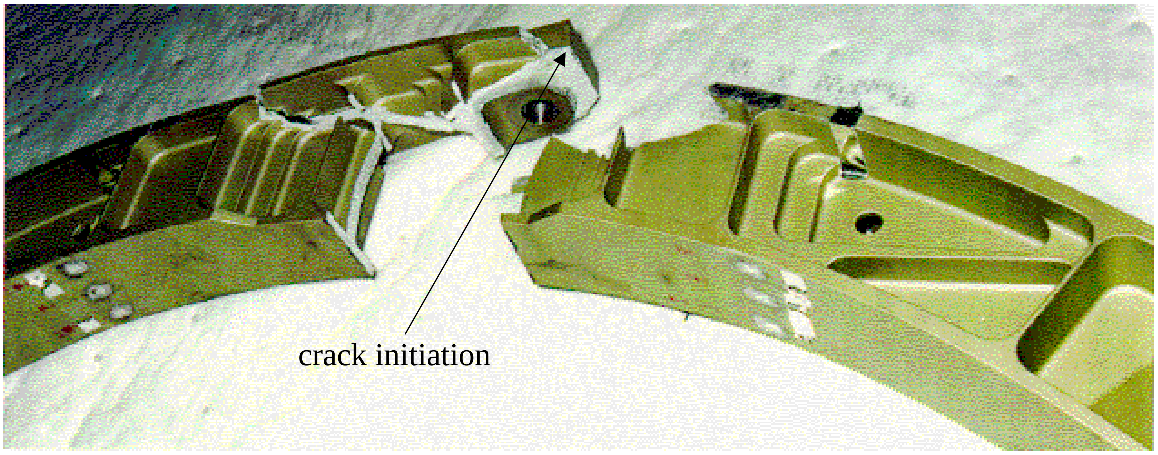
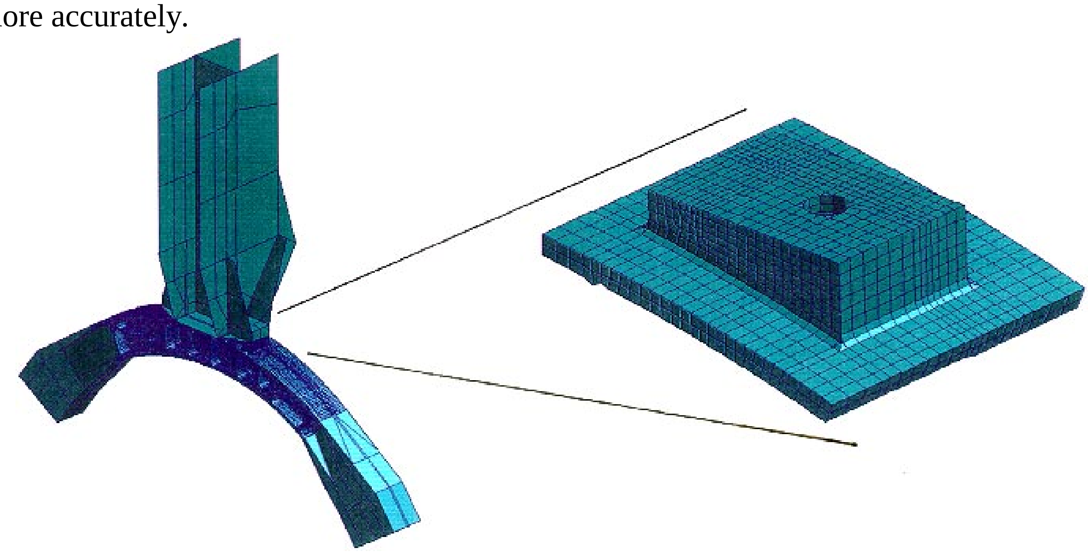


Figure 12. F-16 479 bulkhead test specimen number -7B, post-failure [8]

The fine-grid finite element model of the 479 bulkhead test component[9] is presented in Fig. 13. A coarse-grid dummy vertical tail is attached to the finely meshed upper portion of the bulkhead at the two attach pads, one of which is shown in an expanded view. During the component test program, a horizontal load ram applied force to move the vertical tail to the left and right according to various F-16 spectra. An important result of the finite element analysis of this component was that the results were found to not be symmetric. That is, the stress at the radius resulting from displacement of the tail in one direction was not similar to the stress during displacement in the other direction. The consequence of this was that the spectrum required separation into a tension portion and a compression portion. When the tension spectrum indicated that a load was applied, the tension finite element results were used by MSC/FATIGUE. Similarly, when the compression spectrum indicated a load, the compression results were used. A single loading history and a single corresponding finite element result case could be used in the analysis, but it was expected that the use of two separate conditions would model the test more accurately.



(a) full model (b) vertical tail attach pad (one of two)

Figure 13. F-16 479 bulkhead test component finite element model [9]

Analysis of the bulkhead with MSC/FATIGUE indicated that damage would occur, as expected, at the radius between the bulkhead and the attach pad. This is somewhat deceptive, however, because only the most highly stressed elements of the model (which corresponded to this area) were analyzed in the MSC/FATIGUE run. Analysis of the entire bulkhead could have been attempted, but the computing time necessary to obtain a solution would have been far greater than what was required by analyzing a small area. This suggests that the judgment of the user can potentially influence the results of an analysis, not only with respect to the numerous choices of analysis variables, but in what is included in, and excluded from, an MSC/FATIGUE analysis run. Typically, it would be the most highly stressed elements in a model that would be susceptible to initiation damage. The user must nevertheless be aware that a combination of independent loads might result in a damaging situation otherwise undetectable by a simple review of static finite element results.

Figure 14 presents results of the MSC/FATIGUE analysis of the 479 bulkhead test component. Note that four separate sensitivity analyses have been included in the plot. The dashed lines correspond to the use of the original single spectrum (which assumed a symmetric loading condition), while the solid lines coincide to the more conservative use of two separated spectra. In addition, each load history case included two mean stress corrections – one with the Morrow correction and one with the Smith-Watson-Topper correction. Clearly, the Morrow correction produced more conservative results for this particular situation, and this was likely due to the large compressive stresses experienced at the radius (Smith-Watson-Topper corrections were used in previous analyses because this method is typically more conservative when tensile mean stress dominates).

Unfortunately, MSC/FATIGUE does not currently allow explicit determination of the life-to-failure if crack initiation occurs before the application of a single complete block (this corresponded to 1,000 flight hours in this case). The estimate of 125 hours at a maximum spectrum stress of 38.35 ksi was therefore determined by a simple log-log extrapolation of the data presented in Fig. 14. Note that a LOOPIN analysis predicted a slightly less conservative 340 hours. Two components corresponding to this geometry and load history were tested[8], and the information is also included in Fig. 14. Neither data point corresponds to the initiation of a 0.01 inch crack, but both emphasize that very quick initiation did occur at the radius. MSC/FATIGUE appears to produce good results for this model, in that both the location of damage was correctly predicted and that crack initiation was expected to occur very quickly.

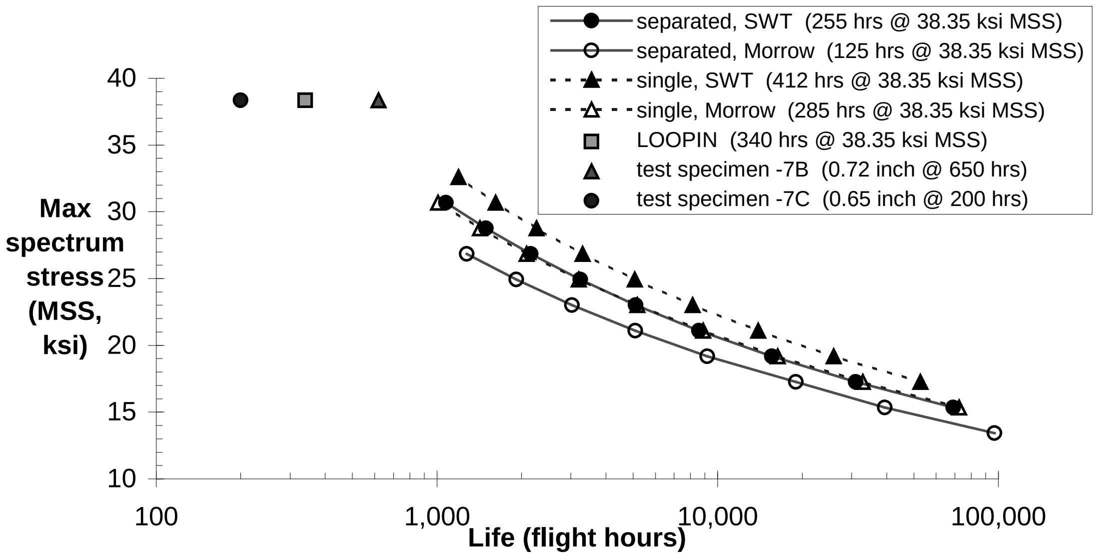


Figure 14. MSC/FATIGUE, LOOPIN, and test results - F-16 479 bulkhead

MSC/FATIGUE IN THE PRELIMINARY DESIGN ENVIRONMENT

The primary purpose of this MSC/FATIGUE evaluation was to determine if the software would be useful during the preliminary design of an aircraft. The previous examples revealed that MSC/FATIGUE is certainly a useful analysis tool, but as an attempt to in some degree determine its full potential, a coarse grid finite element model of a forward fuselage and fuel tank[10] was analyzed. This model contained both shell elements and bar elements, and this required a separate MSC/FATIGUE analysis for each (the software cannot analyze both one-dimensional and two-dimensional elements at one time). The result of the two investigations was that the shell elements were discovered to be more critical than the bars (for the particular loading conditions and spectra), and therefore only shell results are presented below.

A purely hypothetical analysis was attempted by choosing five finite element result cases, with each case corresponding to a different flight condition. These result cases were applied to the model in an MSC/FATIGUE analysis by way of a fictitious loading history (each case was applied independently of one another, as with the simple three-dimensional edge notch analysis above). The results of this MSC/FATIGUE analysis indicated several locations where the structure could potentially be life-limited (see the contour plot in Fig. 15). Again, note that this is a hypothetical example, but the two highlighted areas correspond to locations on the model where cracks would be expected to initiate more quickly than at other locations. If this analysis had been completed during a preliminary design phase, one might have attempted to improve the initial design in order to avoid future cracking problems in the life-limited areas. Such early redesign, resulting from a relatively quick analysis of the model, could avoid significant problems that might occur after additional design, manufacture, and service use. MSC/FATIGUE therefore appears to be a valid candidate for use in preliminary design in that it would allow life-related issues to be addressed during early phases of aircraft development.

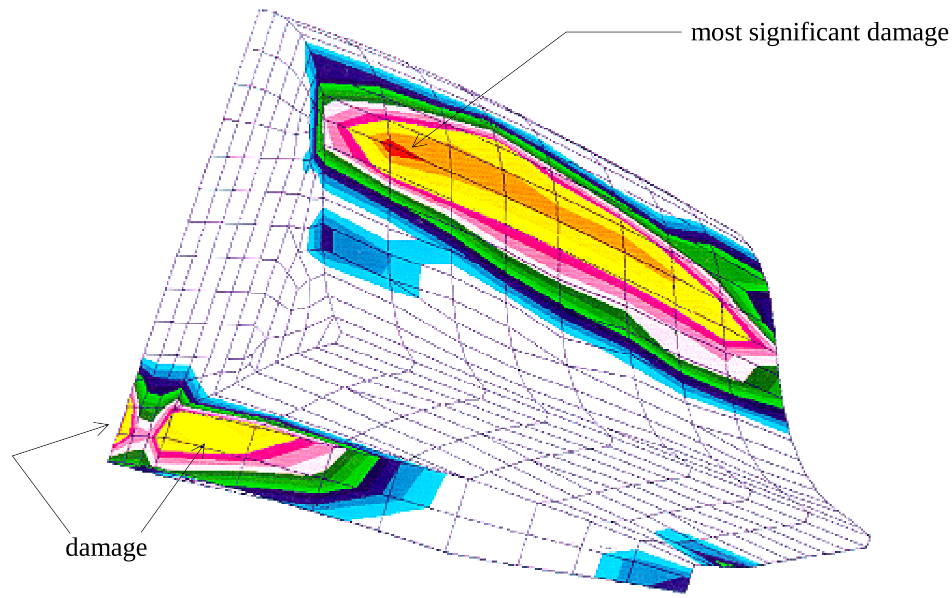


Figure 15. MSC/FATIGUE results - forward fuselage / fuel tank life contour plot

BENEFITS OF LOOPIN VERSUS MSC/FATIGUE

Although this evaluation task indicated that MSC/FATIGUE clearly has a place in the preliminary design environment, it also revealed that current tools (in this case, LOOPIN) should continue to be used in certain situations. When an analysis would benefit from the determination of where on a structure damage may occur, MSC/FATIGUE would certainly be the better tool because of its demonstrated global abilities. The MSC/FATIGUE software could also be used for detailed support analyses, but LOOPIN would likely be a better choice for several reasons. First, as was noted in numerous examples throughout this document, the results obtained with LOOPIN were typically more conservative than those obtained with MSC/FATIGUE. The less conservative nature of the MSC/FATIGUE results was, however, outweighed by the global-analysis abilities of the software (versus the point-analysis abilities of LOOPIN). A detailed support analysis task may require more conservative results, and this would lead to the use of LOOPIN. Second, a LOOPIN analysis for a single documented critical location could potentially take less total time when compared with a complete MSC/FATIGUE analysis. The global ability of MSC/FATIGUE comes at a rather high price, and the details of performing a fatigue analysis on a large model have not yet been worked out. Instead of having just five load cases (as in the previous example) a typical aircraft development program would have somewhere in the range of 100 to 500 load cases. In addition, the load event sequence would contain tens of thousands of points. The time required to complete a full MSC/FATIGUE analysis could potentially be far greater than that needed to compete a similar LOOPIN analysis, in which case LOOPIN would likely be the better choice of analysis tools.

CONCLUSIONS

Several conclusions can be reached from this evaluation of MSC/FATIGUE:

- MSC/FATIGUE crack initiation capabilities are state-of-the-art with regard to both advanced CAE/visualization and current fatigue crack initiation theory,

- fatigue crack initiation predictions compare favorably with those generated with another analytical technique as well as with test data,

- MSC/FATIGUE was demonstrated for detailed analysis,

- MSC/FATIGUE is a candidate tool for durability assessment during preliminary design,

- the primary advantage of MSC/FATIGUE is its ability to locate areas in a structure that may be susceptible to crack initiation, and

- LOOPIN is still a viable tool for crack initiation analyses, most notably in production and support environments when the requirements of fast results and the probable knowledge of damaged locations may not allow for or require a finite-element based analysis.

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