FDE Total Life Project Overview

In 2012 the SAE Fatigue Design & Evaluation Committee initiated the total life project with the objective to improve the prediction of fatigue performance in ground vehicle welded structures. Fundamental to this effort is acknowledgement that both the initiation and the crack growth life need to be accounted for in the prediction. The material chosen for this effort was a low strength, high ductility steel (A36), commonly used in the ground vehicle industry. Loading conditions included both constant amplitude and variable amplitude with both compressive and tensile mean stresses. The loading conditions and material were chosen because they are representative of the most challenging combinations encountered in the ground vehicle industry for crack growth prediction. A number of committee members and organizations contributed to this effort. This included design of a simulated component (test article) modeling of the test article (FEA), prediction of residual stresses, measurement of residual stresses, lab testing and data acquisition, fractography, and fatigue analysis. The group has developed a set of data (loads, material properties, and crack size and shape vs loading cycles) that can be used to benchmark life prediction methods. This includes analysis of the fracture surface to document the crack size and shape as a function of applied loading blocks. Results to date with machined specimens have demonstrated excellent correlation between predicted and experimental results. Key factors in accomplishing this included accounting for crack nucleation life, crack growth life, component residual stress, and plasticity both near the crack tip and ahead of the crack tip as it grows. Properly accounting for plasticity is critical in understanding crack growth of A36 steel under typical ground vehicle loading conditions. This presentation will provide an overview of the project and results to date.

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INTRODUCTION:

The SAE Fatigue Design & Evaluation Committee (FDE) is a mix of engineers and academia that work together to test and develop methods to improve fatigue design. They recognize that fatigue design is not an exact science and are focused on practical engineering solutions that will impact ground vehicle design. They have conducted several challenging fatigue projects over the decades with the objective to identify gaps in our understanding of fatigue and move the technology forward. These projects generally provide data that provides feedback on the accuracy of fatigue predictions. It is important to note that while fatigue design is not an exact science, designers and engineers have become adept at coping with the uncertainty in fatigue design while always trying to improve the process.

Traditionally, the FDE has defined fatigue life as the number of loading cycles to form a crack (crack initiation, N_I) and discounting the time the crack grows before the component no longer will carry a load (crack growth, N_P). One of the challenges in this approach has been the difficulty in defining crack initiation. (AKA: When is a crack a crack?) Most fatigue designers concede that the total life is composed of both initiation and growth ($NT = N_I + N_{P)}$. This is simple in concept but challenging to implement. Actual ground vehicle welded structures often spend a significant portion of their total life in both regions. Fundamental to this current effort is acknowledgement that both the initiation and the crack growth life need to be accounted for in the prediction and that it is necessary to better define crack initiation.

With increasing competition, engineers must produce structures closer to actual targets and take advantage of developing welding technologies. Overdesign and/or undersign of structures must be reduced to compete. In 2012 the FDE initiated the total life project with the objective to improve the prediction of fatigue performance of ground vehicle welded structures. While this project is ongoing, the progress to date needs to be communicated the larger fatigue community beyond the FDE membership. The objective of this presentation is to provide an overview of the project. Details of the load histories, analysis methods, etc. are not included in this report. Some of these are available in publications [1], while other details will be documented in future publications or on the FDE website www.fatigue.org.

TEST METHOD/OVERVIEW

The material chosen for this effort was a low strength, high ductility steel (A36HR), commonly used in the ground vehicle industry. This material is one of the most ductile steels in common use in the industry and the high ductility of this material results in significant local plasticity in fatigue applications. This makes it a challenging material to predict fatigue performance. Four 101.6 mm square bars were purchased by one of the industrial sponsors. Care was taken to assure there was minimal material variation from specimen to specimen. Material test specimens were taken from the bars to provide a single set of carefully developed material properties to use as inputs to life prediction. These were done using at a trusted lab with facility use provided by of one of the industrial sponsors and manpower provided by one of the committee members. Hourglass specimens to determine the strain-life properties and the cyclic stress-strain curve. Crack growth tests were performed on compact tension specimens to determine the crack growth properties. Details of the material characterization are documented separately [1,2].

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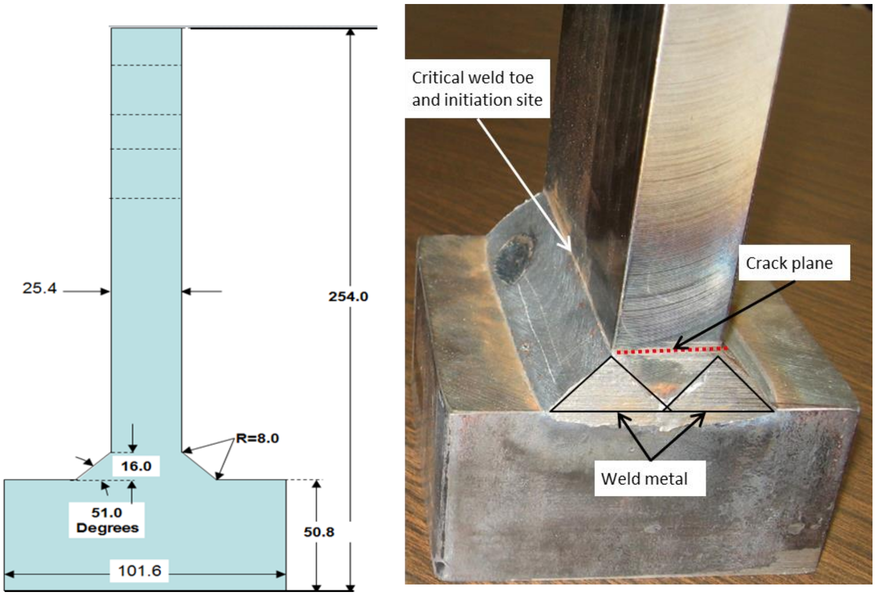

Figure 1. Test Specimen

Rectangular steel blanks were cut from the bars and welded into the geometry shown in Figure 1. Other specimens were then machined into the same geometry as measured on a representative welded specimen. The 51 degree angle and 8 mm radius were measured from representative welds.

There were 2 specimen types used. While the objective was to predict fatigue life on a welded structure, both welded and fully machined specimens were used. This provided an intermediate benchmark without the uncertainties introduced by the welding process. Specimen machining and fabrication was provided by one of the industrial sponsors. Residual stresses were characterized on both specimen types. This was done with surface and subsurface measurements combined with analysis and expert judgment to develop a through thickness residual stress profile to use as input to the life predictions. Residual stress was also measured after a few cycles of loading to determine changes in residual stress resulting from the load history. Several committee members contributed time to do both linear and nonlinear FEA of the test article for comparison to the residual stress results and for input to the life prediction. Details of the specimen, welding parameters, residual stress, and analysis are documented separately [1,2].

The test configuration is shown in Figure 2. Load was applied through a servo controlled hydraulic actuator using a stiffback attached to the bedplate. The specimen was secured to the bedplate. This resulted in a bending load on the T shaped specimen. Loading histories included constant amplitude (R = -1, 0.1, and 0.3) and variable amplitude loading. Two types of variable amplitude load histories were used. One was constructed using blocks of 5,000 constant amplitude cycles at R = 0.1 followed by 40,000 cycles at R = 0.5 with the same maximum load. The other variable amplitude history was constructed from variable amplitude load histories used in previous FDE projects. One repeat of the normalized variable amplitude load history is shown in Figure 3. It was chosen to represent one of the most challenging conditions in the ground vehicle industry for crack growth prediction. Files with these normalized load histories are available on the website www.fatigue.org.

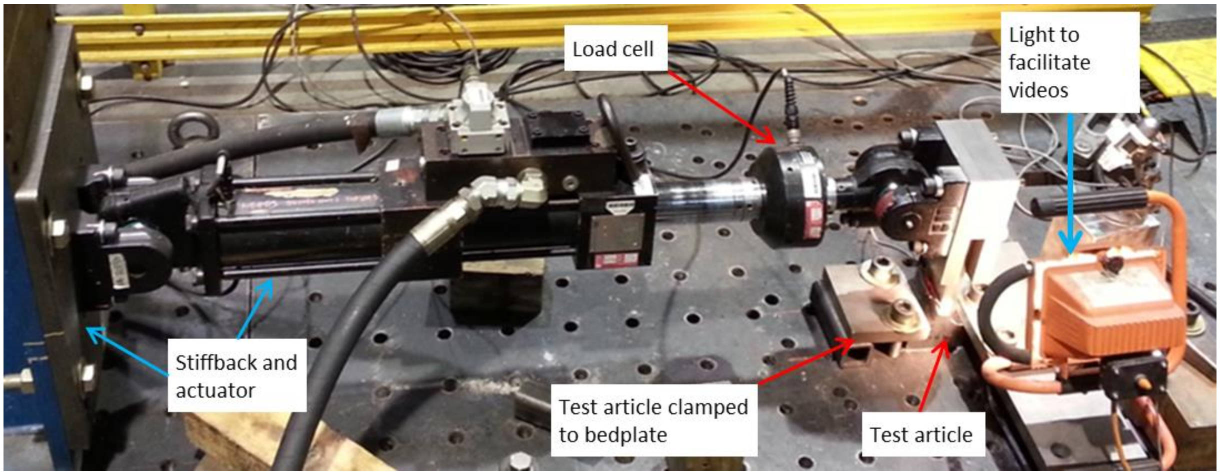

Figure 2. Test Configuration

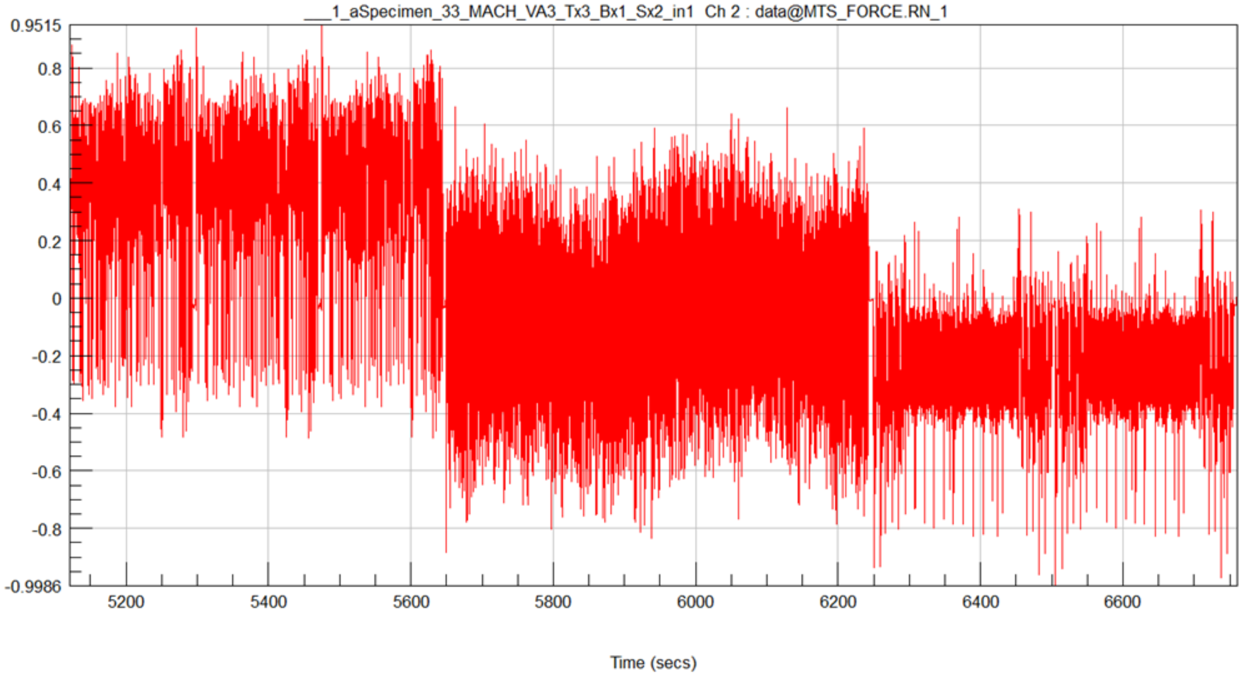

Figure 3. Normalized variable amplitude load history

Applied load and deflection were continuously recorded for each test so that life predictions could be based on actual measured load and would include any variations in the load history that might occur during the test. Also, video was recorded during the tests. This data is available and can be supplied upon request. Specimen failure was defined as the loading cycle when gross yielding occurred before the endpoint of the load reversal was reached. This was generally a ductile failure with gross specimen yielding without fracturing into 2 separate pieces.

Posttest fractography has been completed on some of the specimens and additional work is planned to allow comparison of crack progression with predictions. Figure 4 shows the fracture surface of a specimen loaded with the variable amplitude history. Marker bands identify repeats of the history on these fractures. These provide reference data to use for comparison with the predictions. SEM is being used to measure the distance between the repeats in both directions of crack growth and to track crack growth back to the ignition site. This provides reference data on repeats to initiation, crack growth vs repeat number, and crack aspect ratio vs life. Notice that cracks formed and grew on both sides of this specimen. This changes specimen compliance during the test. This compliance change needs to be considered in life predictions.

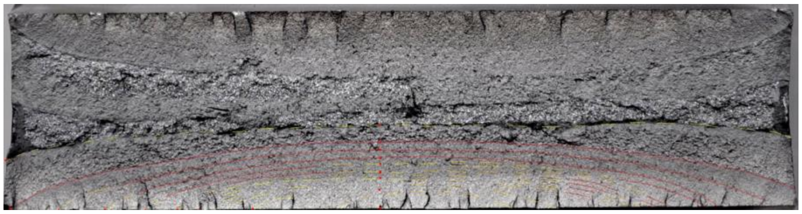

Figure 4. Fracture surface from block load history

RESULTS/DISCUSSION

Much works remains to complete this project but enough data has been collected to allow comparing predictions to actual life. The intent is to use the test results as a basis to compare to predicted life using the commonly available methods and compare results. At this time analysis results have only been reported for one method. Details of this method are in reference [1]. Volunteers to perform life predictions with other methods would be welcomed. Details necessary to do life prediction with other methods can be requested by contacting the FDE through the website www.fatigue.org. Results from method 1 are shown in Figure 5. The correlation between experimental and analytical results was considered excellent for total life. Key factors in accomplishing this included accounting for crack nucleation life, crack growth life, component residual stress, and plasticity both near the crack tip and ahead of the crack tip as it grows.

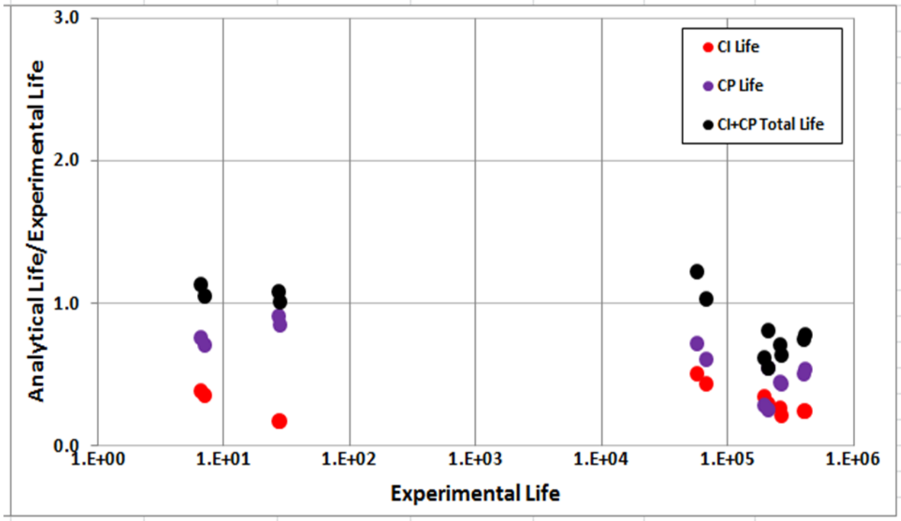

Figure 5. Analytical vs experimental life for method 1

SUMMARY

While the work is not yet complete and the committee has not yet reported final conclusions, several comments are presented for consideration and discussion.

- The group has developed a set of data (loads, material properties, and crack size and shape vs loading cycles) that will be useful to benchmark life prediction methods.
- Additional documentation is required to facilitate distribution and long term usefulness of this data.
- Methods combining initiation life with crack growth predictions provide the potential to reduce uncertainty in predicting fatigue performance and to be more accurate than those considering only initiation life or crack growth life.
- Accounting for plasticity will be essential in predicting fatigue life in ductile material such as A36 steel under typical ground vehicle loading conditions.
- Additional methods should be applied to this data for comparison to method 1.

ACKNOWLEDGEMENTS

It is important to note that the author is reporting this work as his contribution to the FDE committee activity and that this is not presented as his work. A project of this scope could only happen with support of the many individuals on the committee. In the span of this program many individuals have contributed and are continuing to contribute to understanding fatigue.

The project would not have progressed this far without the leadership, perseverance, and dedication of Tom Cordes and the support of industrial sponsors with direct financial or facility contributions. These sponsors include Caterpillar, John Deere, MTS Systems Corporation, Element, Lambda, and HBM nCode. In addition; numerous committee members contributed time and expertise to make this a successful project. These include Al Conle, Eric Norton, Eric Johnson, Gregg Glinka, Haley Brown, Matt Campbell, Paul Prevey, Peter Huffman, Phil Dindinger, and Semyon Mikheevskiy.

REFERENCES

[1] S. Mikheevskiy, G. Glinka, T. Cordes, Total life approach for fatigue life estimation of welded structures, presented at 3rd Conference on Material and Component Performance under Variable Amplitude Loading, VAL2015, publication pending

[2] FDE meeting presentations, not yet published