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Fracture Mechanics and Its Application in the Fatigue Behavior of Reinforced Welded Hand-Holes in Aluminum Light Poles

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Abstract

Predicting fatigue life of a given specimen using analytical methods can sometimes be challenging. An approach worth considering for this prediction involves employing fracture mechanics. Fracture mechanics can complement both laboratory experiments and finite element analysis (FEA) in estimating fatigue life of a given specimen, if relevant. In the case of aluminum light poles containing a welded hand-hole, the fatigue life has not yet been thoroughly predicted. The University of Akron has conducted a comprehensive fatigue study on aluminum light poles through various means, albeit without of predicting of said fatigue life of the specimens. AFGROW (Air Force Growth) can be used as a fracture mechanics software to predict fatigue life. ABAQUS was used (for FEA) in conjunction with the AFGROW analysis. The purpose of this study was to ultimately predict the life of the specimens tested in the lab and was achieved with various models including hollow tube and plate models. The plate model process was ultimately found to be the best method for this prediction, yielding results that mimicked the data from the laboratory. Further application for this form of fracture mechanics analysis is still yet to be determined, but for the sake of aluminum light poles, it is possible to predict the fatigue life and utilize said prediction in the field.

Keywords

Fracture Mechanics, Finite Element Analysis, AFGROW, Fatigue Analysis, Structural Analysis

1. Introduction

The general problem of fracture has plagued society as long as there have been mad-made structures and very well may be worse today than it was in previous centuries due to how advanced technology has gotten. With this advancement in technology, our understanding of how materials and structures fail has needed to expand and thus the field of fracture mechanics has helped to offset some potential dangers [1].

The presence of a crack in a part intensifies the local stress in the area around the crack tip and may precipitate failure. A stress intensity factor can be used in this form of analysis to help characterize the local stress field and is calculated as a function of the crack size, part geometry and applied stress. Failure will occur when the stress intensity factor exceeds the material fracture toughness, and it is at this point the crack will grow in a rapid and unstable way until failure [2].

The theory of fracture mechanics was first introduced by an English aeronautical engineer, A. A. Griffith, during World War I as a way to explain the failure of brittle materials. The problem presented to Griffith was that the stress at the end of a sharp crack appeared to approach infinity utilizing the theoretical process of the time. According to such calculations, any structure containing a crack should fail no matter the size of the crack or magnitude of the load. To solve this problem, Griffith developed a thermodynamic approach that assumed the growth of a crack requires the creation of surface energy, which is supplied by the loss of strain energy accompanying the relaxation of local stresses as the crack advances. Failure would occur when the loss of strain energy is sufficient enough to provide the increase in surface energy [3].

Griffith's theory was expanded upon by a group under G. R. Irwin at the U. S. Naval Research Laboratory during World War II. Irwin and his colleagues developed a modified version of Griffith's approach by reformulating it in terms of stress rather than energy. This ultimately resulted in a new material property, fracture toughness, which is denoted by a "K" and is now universally accepted as the defining property of fracture mechanics [3].

The general application of fracture mechanics can be broken down into three major areas. These include design, material selection/alloy development, and determining the significance of defects. Ancillary areas of application include monitoring/control and failure analysis [4].

A few previous studies used a fracture mechanics approach to predict fatigue life. A study conducted at INEGI, University of Porto, Rua utilized a crack growth analysis to assess the residual fatigue life of components containing an internal flaw. Their approach was applied to a notched plate made of P355NL1 steel. It was found in this study that the predicted S-N data available for the notched steel showed a very good agreement between predicted and experimental data [5]. In addition, a study funded by the "General Program of National Natural Science Foundation of China" analyzed marine structures using a fatigue crack growth process, but unfortunately the study yielded no concrete conclusions and only reported recent developments [6].

Early development in using fracture mechanics to predict fatigue life at George Washington University, presupposed the existence of a single flaw of "critical" size and slow propagation, under repeated cyclic loading, represents the relevant damage mechanism that governs "fatigue" until the flaw has grown to an unstable size. They asserted that utilizing fracture mechanics in the context of fatigue provides the most accurate representation of the fatigue process. This entire exploration ultimately delves into various facets of the fatigue process in connection with the fundamental principles of fracture mechanics [7]. A large amount of research since the publication of this paper has been conducted.

Kanninen investigated the compatibility of static and dynamic approaches to crack propagation, sighting key differences between the two. In addition, the importance of integration experimental and computational work in the fracture mechanics field was discussed. From this study, it was concluded that the static and kinetic (dynamic) approaches are entirely compatible as long as reflected stress waves do not reach the crack tip prior to crack arrest. But, when that was not the case, the kinetic approach was stated to be used [8].

Fatigue crack growth rate was analyzed by the University Kebangsaan Malaysia (UKM) using dual-phase steel under spectrum loading based on entropy generation. It was stated that based off the second law of thermodynamics, fatigue crack growth was related to entropy gain because of its irreversibility. Temperature evolution and crack lengths were simultaneously measured during fatigue crack growth tests until failure and the results indicated a significant correlation between fatigue crack growth rate and entropy. This result was the basis for model development and was found to be able to determine the characteristics of fatigue crack growth rates, particularly under spectrum loading. Results showed that the proposed model could accurately predict the crack growth rate in all cases [9].

A team at MIT explored a machine-learning approach to predict a fracture process connecting molecular simulation into a physics-based data-driven multiscale model. Using an Atomistic modeling and novel image-processing approach, they compiled a comprehensive training dataset featuring fracture patterns and toughness values for different crystalline orientations. It was found that assessments of the predictive power of the machine-learning model agreed with typical fracture patterns and fracture toughness values. The model was presented in a way for potential applications to be applied in material design [10].

Propagation of a welded toe crack (under cyclic loading) was predicted using fracture mechanics in a study conducted at Eindhoven University. The propagation life of a welded connection is typically spent as a short crack that behaves differently than a long crack. The paper presented by this university bypassed the inconvenience of the traditional long process by making use of the square root area parameter proposed by Murakami and created a linear elastic fracture mechanics-based fatigue crack growth model, formulated for physical short and long cracks. They found it was possible to predict average fatigue life of the welds within a reasonable bound [11].

A research team at Southeast University, Nanjing studied the fracture and fatigue analyses of cracked structures using the interactive method. The study revolved around analyzing a structure containing no cracks by using traditional finite element methods. The crack was analyzed using an analytical solution and other numerical solutions effective to solving crack problems. In this study, the iterative method was developed and used to obtain stress intensity factors to simulate fatigue crack propagation and found that the computed stress intensity factors for racks using the method aforementioned are in good agreement with analytical solutions or empirical solutions. It was also found that the whole crack growth path up to a failure point (in a structure) can be easily and efficiently simulated using this method [12].

None of the studies aforementioned utilized AFGROW (Air Force Growth) as an approach to fracture mechanics in fatigue analysis, which was the program that was predominantly used in this study, along with some FEA (finite element analysis) from ABAQUS. AFGROW is a damage tolerance analysis framework that allows the user to analyze fatigue crack growth, crack initiation and fracture to predict the life of metal structures. The program itself is very user friendly and flexible and is one of the most widely used and efficient crack growth life prediction programs available today. There are over 30 different crack geometrics/lading conditions in the classic stress intensity factor library. These include bending, bearing loading, and axial for many cases [13]. AFGROW provides clarification on the program's life prediction methodology at reference [14].

This fracture mechanics analysis was conducted throughout multiple studies completed at the University of Akron, first by Ali Daneshkhah and Clark Schlatter, then continued by Cameron Rusnak. The studies were on aluminum light poles, each exploring a different avenue in accordance with the Aluminum Design Manual (ADM) [15]. Schlatter conducted the original study on 10-inch diameter light poles with a "typical" cast reinforcement stressed under cyclic loading and Rusnak continued the study focusing on different geometries and reinforcement practices. Each of the studies used FEA in ABAQUS in conjunction with laboratory experiments to explore stress concentrations [16] [17] [18] [19].

In prior investigations, fracture mechanics analysis was exclusively applied to a particular "plate" configuration and permanently restricted to steel as the material. With regard to aluminum (particularly in light poles), no in-depth prediction analysis has been conducted. The purpose of the study was to fill in the gaps and give a method of approach when trying to predict the fatigue life of aluminum light poles. The process can then be utilized by engineers to indicate a pole that might possibly fail given its fatigue life.

2. Method

The utilized process of the fracture mechanics analysis evolved over time from an initial hollow tube model and ultimately into a "plate" with FEA from ABAQUS. All fracture mechanics models were created in AFGROW (initial crack beta correction, crack manipulation and plate). Any supplemental FEA was conducted in ABAQUS in addition to Microsoft Excel which was utilized to visualize the data collected. The method of approach varied per each type of model (explained in later sections). Loading was applied in AFGROW and was comparable to laboratory experiments from the previous studies conducted at the University of Akron aforementioned. Boundary conditions were used in the direction in which the loads were not applied. Material properties were representative of Aluminum alloy 6063-T6. The process in which the fracture mechanics analyses were utilized are described in the following sections. The data was presented in the form of figures and tables containing correlated points along with their corresponding stress ranges, originating from both the laboratory [7] [8] [9] [10] and the AFGROW analysis. Figures present the "y" axis as the stress range in MPA and the "X" axis represents the number of cycles to failure (both predicted and data collected).

Figures regarding the data/results of the fracture mechanics models are presented similar to each other, that being as S-N curves (data points associated) and compared to ADM standards [15]. Each of the charts is in units of Mpa (labeled as "Stress Range (Mpa)") vs number of cycles to failure (labeled as "Cycles"). Scaling is consistent for all of the figures. In the tables, specimen indicates the specimen number, N indicates the number of cycles to failure AFGROW predicted (DNS states the model did not start/run), stress fraction was a fractional value implemented in AFGROW, and stress range was predicted by AFGROW. The stress fraction itself was initially used as a fractional multiplier in AFGROW in order to attempt to replicate the lab results, but later was changed to a constant value. All ABAQUS models built for the sake of this fracture mechanics model had similar boundary/loading conditions to that of the four-point bending aluminum light pole studies [7] [8] [9] [10] conducted at the University of Akron. Observations for each of the respective model groups are discussed in the Observations and Conclusions section.

2.1. Initial Crack Model and Process

The initial models created contained a small initial crack in the cross section of a hollow tube. Models were compared to the 10-inch diameter standard reinforced hand-hole specimens in addition to the 10-inch diameter unreinforced specimens. The tubes of the models were 10-inch in diameter (consistent with previous studies) with a thickness of 0.25-inch and a small initial surface flaw of 0.07-inch. A sample of what one of the initial break models looked like can be seen in **Figure 1**. Crack growth properties in AFGROW were calculated and represented using the Forman Equation as derived in the program. The loading was determined by this equation and the Forman variable equated to 0.199. Representation of the equation used is as follows and can be seen in Equation (1).

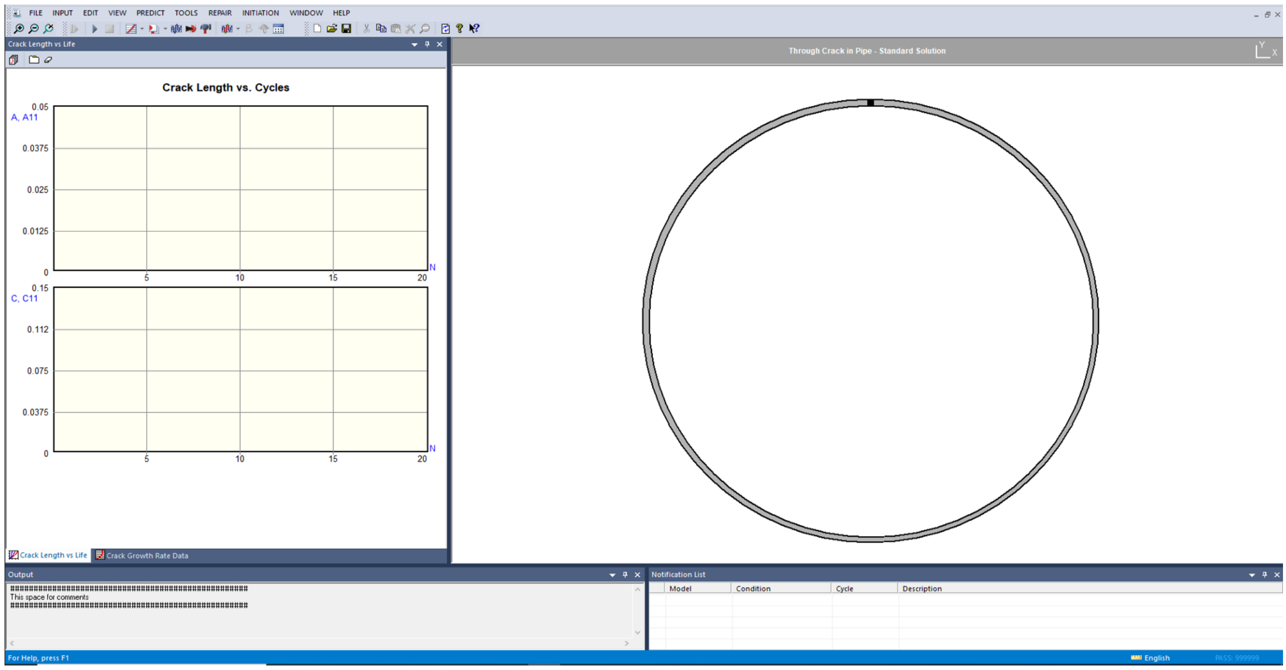

Figure 1. AFGROW interface for initial crack model.

In the case of Equation (1), M represents the moment applied, Ro is the outer radius and Ri is the inner radius.

$$\sigma = 4MRo \Big/ \left(\pi \left(Ro^4 - Ri^4 \right) \right). \tag{1}$$

2.2. Beta Correction Models

After initial inspection of the small defect models, it was hypothesized that a beta correction factor could be used to better replicate the lab data. Beta correction factors are used in order to account for the varying levels of stress along a point of interest. They consider the stress intensity factor "K" and provides it in terms of a geometry correction factor "β" (Equation (2)) where:

$$\beta = \frac{K}{\sigma\sqrt{\pi x}} \tag{2}$$

with x representing the crack length that is of interest. Beta values can be adjusted independently for compressive and tensile loading in all cases [13]. From the previous studies, the area of interest is around the 9 o'clock position of the traditionally reinforced specimens or nonreinforced specimens. In the flush specimens, this area of interest was at the inside "corner" of the reinforcement. The variations in stress concentrations were taken from the ABAQUS models. A path along the area these correction factors were taken can be seen in **Figure 2** and **Figure 3**. **Table 1** represents the beta correction factors for each model used and "r" represents the distance along the path taken from ABAQUS and "S" is the stress concentration per respective location from the ABAQUS models to be used in AFGROW.

Table 1. Beta correction factor table.

#	10 in NI (point of break transversely)			#	10 in Flush (corner of inside reinforcement)		
	r	S (To AFGROW)	S (ABAQUS)		r	S (To AFGROW)	S (ABAQUS)
0	0.000	1.000	58.752	0	0.000	1.000	15.361
1	0.301	0.747	43.910	1	0.108	1.177	18.088
2	0.553	0.513	30.117	2	0.217	0.932	14.319
3	0.865	0.347	20.408	3	0.340	0.808	12.408
4	1.127	0.229	13.465	4	0.464	0.721	11.080
5	1.392	0.158	9.265	5	0.597	0.650	9.989
6	1.656	0.108	6.333	6	0.730	0.603	9.264
7	1.924	0.075	4.390	7	0.862	0.561	8.623
8	2.184	0.055	3.223	8	0.994	0.536	8.226
9	2.445	0.041	2.392	9	1.126	0.512	7.867
10	2.707	0.035	2.067	10	1.257	0.499	7.667
11	2.968	0.023	1.339	11	1.389	0.487	7.487
12	3.230	0.019	1.137	12	1.521	0.482	7.404
				13	1.652	0.477	7.333
				14	1.784	0.476	7.317

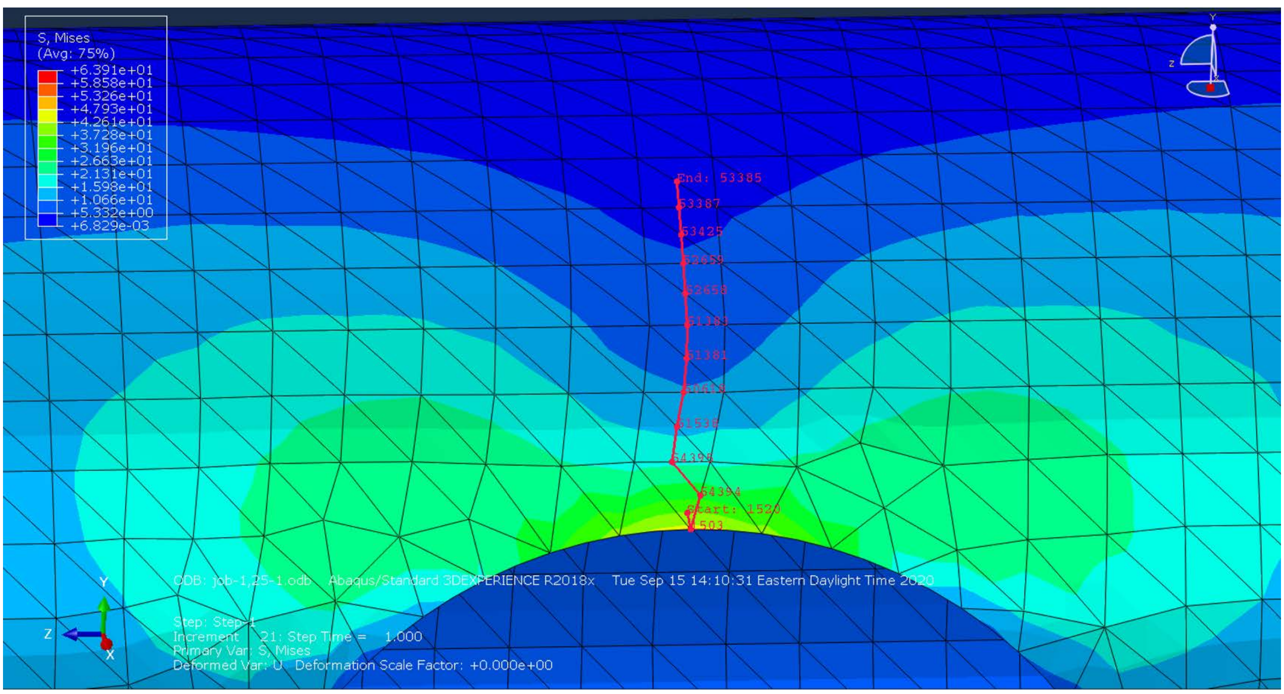

Figure 2. Path for beta correction factor from no insert.

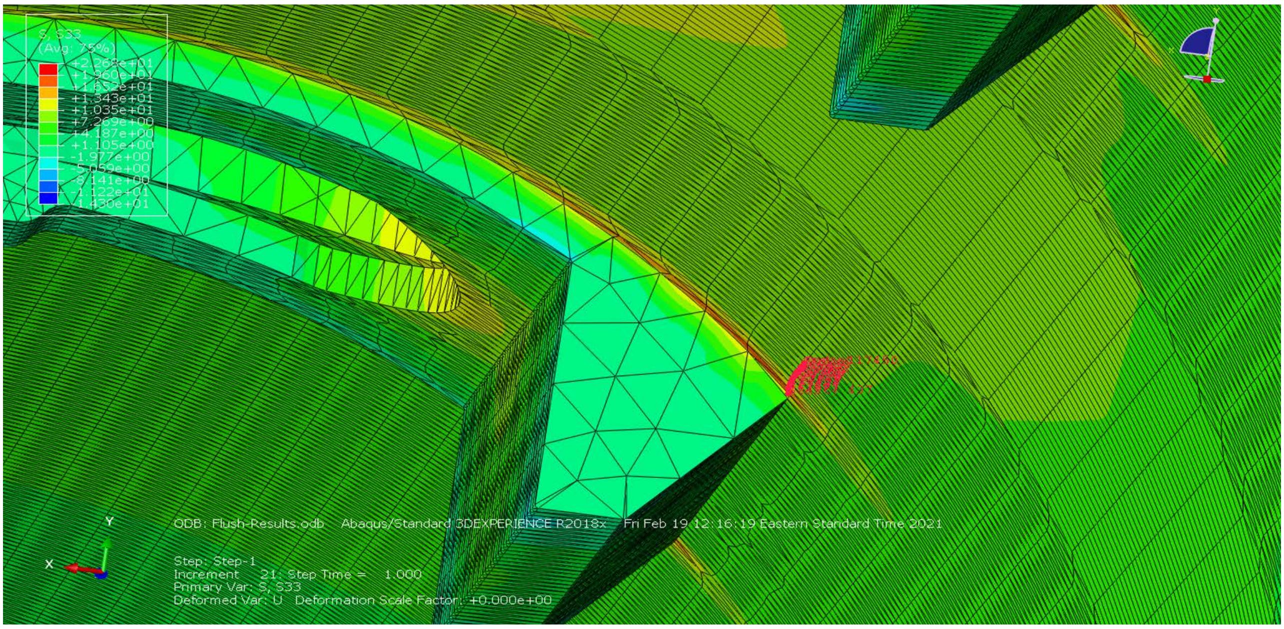

Figure 3. Path for beta correction factor from flush insert.

2.3. Crack Manipulation Models

An initial crack manipulation analysis was conducted to examine how sensitive the predicted fatigue life was to the change in the initial crack size within AFGROW. For this analysis, both the no insert and flush insert specimens were considered. The corresponding initial crack sizes were 0.01-inch, 0.04-inch 0.07-inch (what was used in the original initial crack models), 0.1-inch and 0.14-inch. "Stress Fraction" was abbreviated to SF and "Stress Range" was abbreviated to SR. The beta correction factor previously mentioned was used in conjunction to the initial crack manipulation in these models.

2.4. Plate Models

The final fracture mechanics models generated in AFGROW came in the form of separate plate models. Analysis was conducted on both a partial and through crack in a plate (separate models) and was compared to the typical specimens containing a cast insert that was welded to the outside of the pole. Plates were used to account for the weldment around the hand-hole. Typical cast specimens/models were used as they are the most common out in the field. The process consisted of first taking the FEA of a standard specimen, converting the stress concentration around the hand-hole into the nominal stress that would be on the face of the weldment around the hand-hole and accounting for the nominal stress that was calculated in AFGROW while using the different stress ranges collected from the lab. Ultimately, a prediction from AFGROW would be given after all inputs were satisfied.

The first step was to collect the stress concentrations from the FEA in ABAQUS. The predominant section of interest (area surrounding the cast hand-hole) model was used. In the ABAQUS model, a path was created from the 3 to 12 o'clock position counterclockwise around the center of the reinforcement in the hand-hole in order to analyze the individual stress concentrations of the area. Figure 4 shows the section of interest in ABAQUS. All of the different stress concentrations were found including the lateral, longitudinal, and transverse stresses along with their corresponding shears.

The conversion of the stress ranges into the nominal stress that would account for the weldment was the next step. The conversion was completed by transferring the lateral and transverse stress concentrations into a 45-degree angle. While welding practices are not perfect, the 45-degree angle most closely represents it. Calculations were completed by using simple triangles and geometry, using a depth of 0.5-inch and an area of the weld (in the triangle) was found to be 0.0625-inch. Nominal stress was then calculated and found to be 66.965 which was then used as the stress fraction in AFGROW.

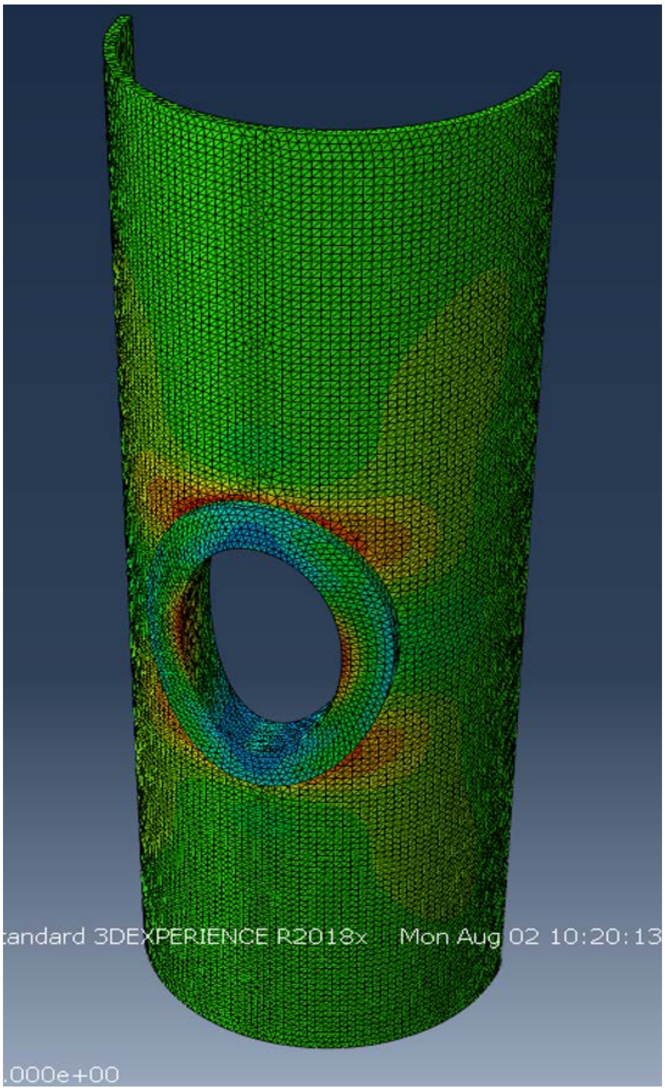

Figure 4. Sample section of ABAQUS model used for plate analysis.

The next and final step was the AFGROW analysis. Both a plate containing a through crack and a plate with a partial crack were constructed. These were created in the same manner (other than that of the crack itself). A classic model was used with a width of 10-inch (in an attempt to keep consistent to the diameter of the pole, but this width was almost negligible), a thickness of 0.25-inch (consistent with the lab experiments) a stress fraction of 66.965 as calculated prior and the very small through and partial for each model. Crack sizes were very small, each being 0.01-inch for their corresponding model. The material property used was that of the "Halter-T Method". Material property for these models was found to be negligible, thus the default was used. Stress multiplication factor (SMF) varied depending on the stress range used in the lab and was at constant amplitude. There was no beat correction or "K" solutions (as denoted in AFGROW) used for this specific analysis. Sample figures for the corresponding through and partial crack models can be seen in Figure 5 and Figure 6.

3. Results

3.1. Initial Crack Model and Process

In general, the initial break models were relatively basic with imputed values for the material properties. Table 2, Table 3, Figure 7 and Figure 8 demonstrate the results of the initial break models and are as follows:

Figure 5. Through crack model in AFGROW.

Figure 6. Partial crack model in AFGROW.

Table 2. Tabulated results of the 10-inch pipe with a small defect.

Specimen #	N	Stress Fraction	Stress Range (Ksi)	Stress Range (Mpa)
1	DNS	0.21	2.00	13.79
2	**DNS**	0.32	3.00	20.69
3	**DNS**	0.38	3.60	24.82
4	1,602,356	0.48	4.50	31.03
5	741,223	0.60	5.70	39.30
6	535,396	0.67	6.30	43.44
7	264,684	0.82	7.80	53.78
8	191,291	0.91	8.60	59.30
9	159,240	0.96	9.10	62.74
10	89,561	1.14	10.80	74.47
11	70,279	1.23	11.60	79.98

Table 3. Tabulated results of the 10-inch pipe with a small defect with no insert.

Specimen #	N	Stress Fraction	Stress Range (Ksi)	Stress Range (Mpa)
1	2,960,424	0.50	2.50	17.24
2	**1,475,904**	0.62	3.10	21.37
3	**1,091,226**	0.67	3.40	23.44
4	601,613	0.81	4.10	28.27
5	442,285	0.89	4.48	30.89
6	273,993	1.03	5.20	35.85
7	109,379	1.37	6.90	47.58
8	75,463	1.52	7.64	52.68
9	52,844	1.69	8.50	58.61

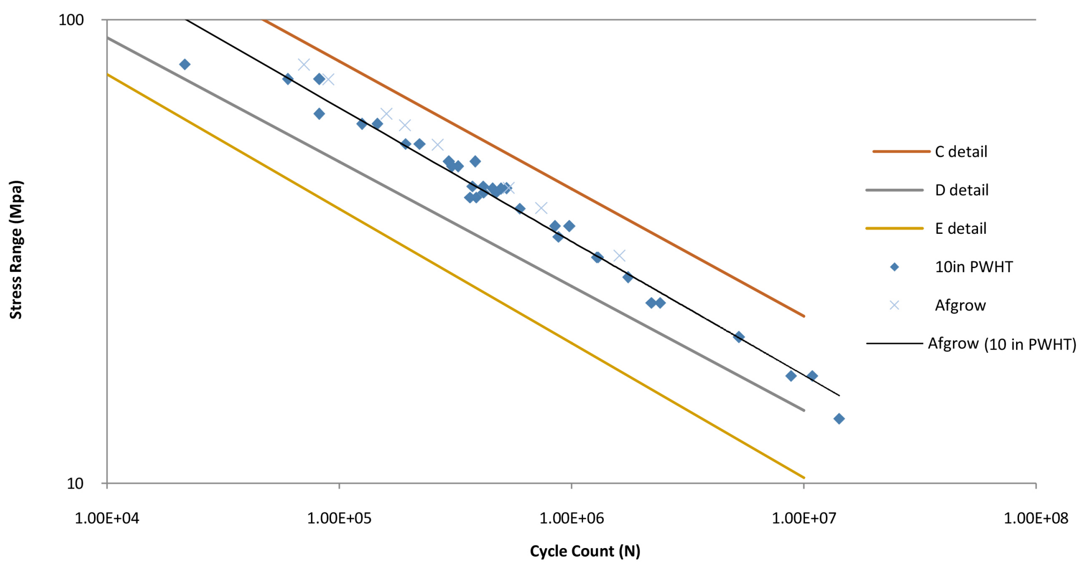

Figure 7. 10-inch reinforced AFGROW analysis vs Lab results.

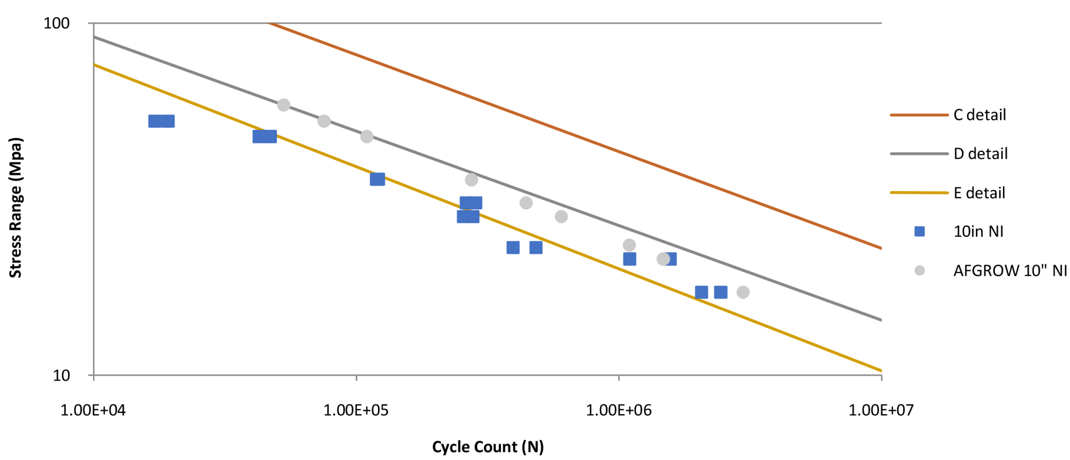

Figure 8. 10-inch no insert AFGROW analysis vs lab results.

3.2. Beta Correction Models

Stress fractions for the beta correction models were calculated in the same manner as the initial crack models. Results from the AFGROW beta correction analysis can be seen in Table 4, Table 5, Figure 9 and Figure 10 and are as follows.

3.3. Crack Manipulation Models

An initial crack manipulation analysis was conducted to examine how sensitive the predicted fatigue life was to the change in the initial crack size within AFGROW. For this analysis, both the no insert and flush insert specimens were considered. The corresponding initial crack sizes were 0.01-inch, 0.04-inch 0.07-inch (what was used in the original initial crack models), 0.1-inch and 0.14-inch. "Stress Fraction" was abbreviated to SF and "Stress Range" was abbreviated to SR. The beta correction factor previously mentioned was used in conjunction to the initial crack manipulation in these models. Table 6, Table 7, Figure 11 and Figure 12 demonstrate the results and are as follows:

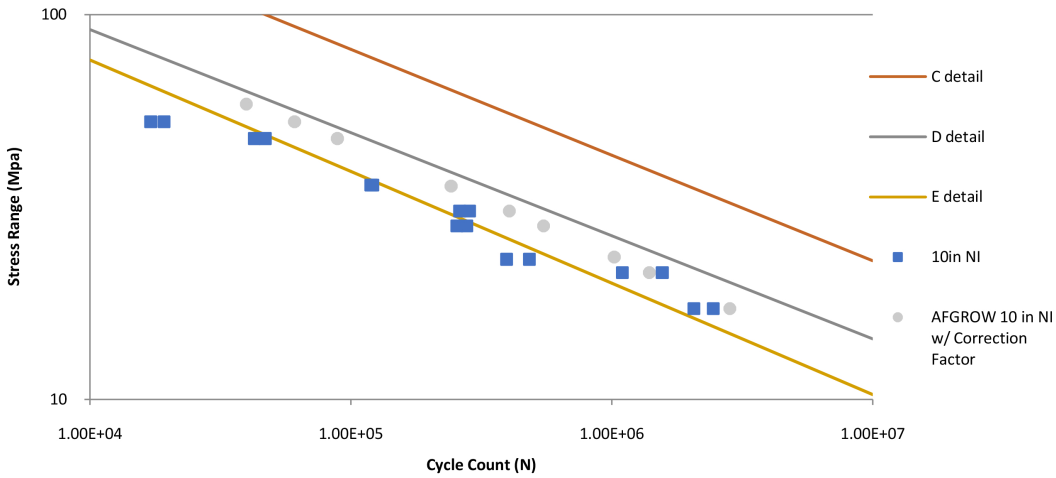

Figure 9. 10-inch no insert AFGROW analysis with a beta correction vs lab results.

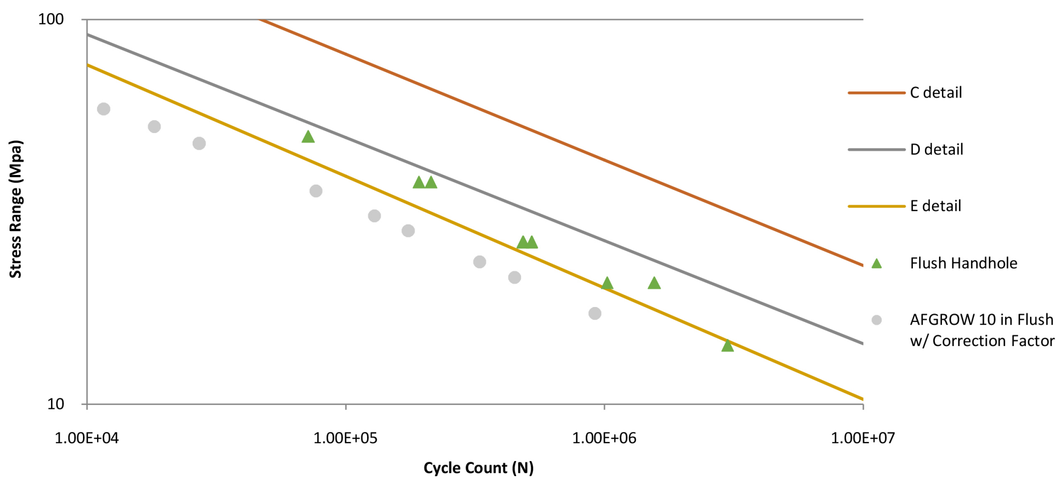

Figure 10. 10-inch flush AFGROW analysis with a beta correction vs lab results.

Table 4. Tabulated results of the 10-inch pipe with a beta correction.

Specimen #	N	Stress Fraction	Stress Range (Ksi)	Stress Range (Mpa)
1	2,825,856	0.50	2.5	17.24
2	1,389,619	0.62	3.1	21.37
3	1,022,308	0.67	3.4	23.44
4	545,772	0.81	4.1	28.27
5	404,145	0.89	4.5	30.89
6	242,320	1.03	5.2	35.85
7	88,839	1.37	6.9	47.58
8	60,921	1.52	7.6	52.68
9	39,682	1.69	8.5	58.61

Table 5. Tabulated results of the 10-inch flush specimens with a beta correction.

Specimen #	N	Stress Fraction	Stress Range (Ksi)	Stress Range (Mpa)
1	915,334	0.50	2.5	17.24
2	447,985	0.62	3.1	21.37
3	328,736	0.67	3.4	23.44
4	174,418	0.81	4.1	28.27
5	128,708	0.89	4.5	30.89
6	76,627	1.03	5.2	35.85
7	27,169	1.37	6.9	47.58
8	18,172	1.52	7.6	52.68
9	11,615	1.69	8.5	58.61

Table 6. Tabulated results of 10-inch no inset with beta correction and crack size change.

#	N (0.07)	N (0.01)	N (0.04)	N (0.10)	N (0.14)	SF	SR (ksi)	SR (Mpa)
1	2,825,856	DNS	3,261,092	2,605,974	2,428,517	0.50	2.5	17.24
2	1,389,619	DNS	1,606,802	1,280,084	1,191,815	0.62	3.1	21.37
3	1,022,308	DNS	1,183,360	941,151	875,800	0.67	3.4	23.44
4	545,772	1,017,682	633,536	501,637	466,161	0.81	4.1	28.27
5	404,145	758,465	469,946	371,091	344,549	0.89	4.5	30.89
6	242,320	461,013	282,823	222,017	205,745	1.03	5.2	35.85
7	88,839	176,120	104,898	80,832	74,444	1.37	6.9	47.58
8	60,921	123,551	72,411	55,205	50,655	1.52	7.6	52.68
9	39,682	83,896	47,765	35,672	32,488	1.69	8.5	58.61

Table 7. Tabulated results of 10-inch flush with beta correction and crack size change.

#	N (0.07)	N (0.01)	N (0.04)	N (0.10)	N (0.14)	SF	SR (ksi)	SR (Mpa)
1	915,334	DNS	1,213,880	793,421	706,434	0.50	2.5	17.24
2	447,985	DNS	596,834	387,360	344,203	0.62	3.1	21.37
3	328,736	DNS	439,069	282,858	251,949	0.67	3.4	23.44
4	174,418	567,675	234,481	150,062	132,795	0.81	4.1	28.27
5	128,708	423,941	173,716	110,489	97,592	0.89	4.5	30.89
6	76,627	258,812	104,302	65,461	57,582	1.03	5.2	35.85
7	27,169	99,842	38,113	22,789	19,722	1.37	6.9	47.58
8	18,172	70,309	25,993	15,053	12,877	1.52	7.6	52.68
9	11,615	48,411	17,110	9433	7917	1.69	8.5	58.61

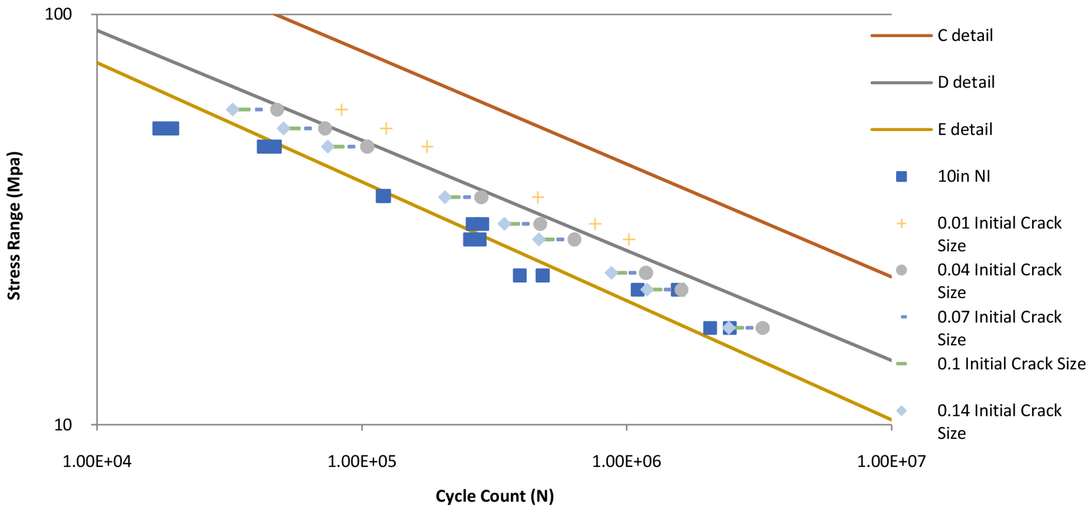

Figure 11. 10-inch no insert with a beta correction and crack size change vs lab results.

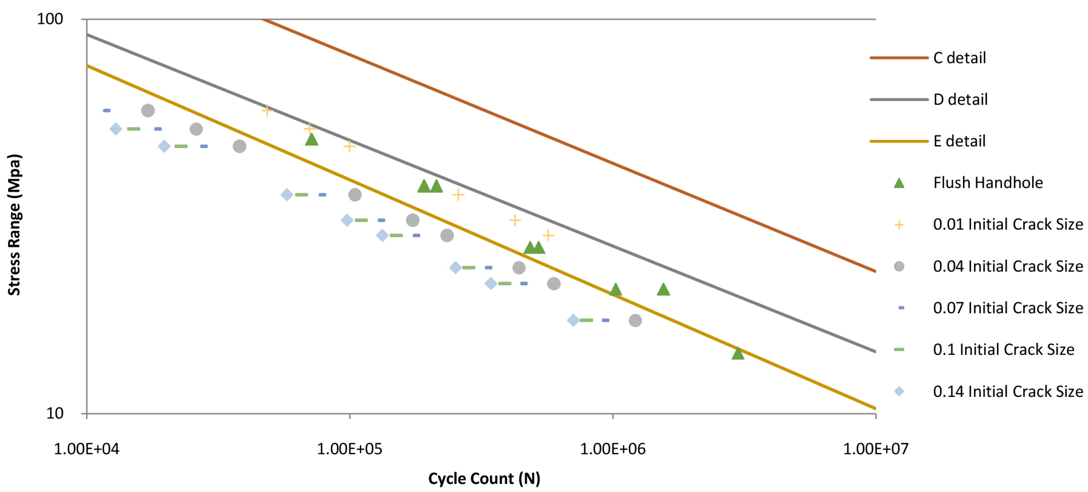

Figure 12. 10-inch flush with a beta correction and crack size change vs lab results.

3.4. Plate Models

The charted results of the plate models can be seen in Figures 13-15. All models were compared to the typical cast insert that was welded to the outside of the pole (present in references [16]). These applicable data points were used as they were relevant to this fracture mechanics analysis was and was the initial catalyst in the search to see if the fatigue life can be properly predicted. Figure 14 depicts the raw results of the through crack and compares it to the data collected in the lab. Figure 15 depicts the raw partial crack analysis, along with a 1.12 multiplication factor of the results to account for the partial crack and compares it to the data collected in the lab. Figure 15 depicts all of the results plotted together and compares it to lab data.

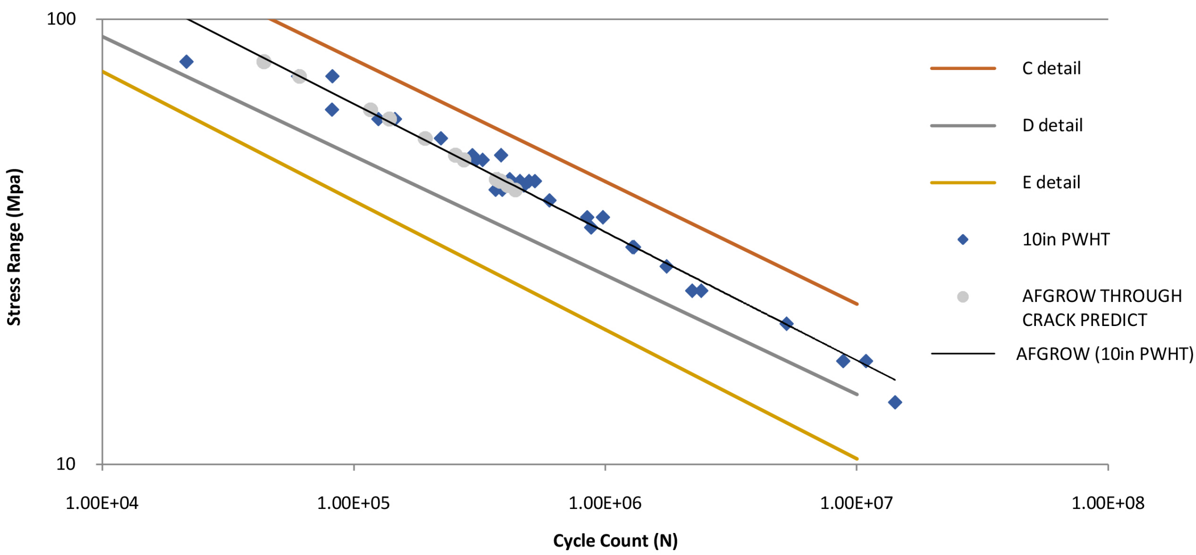

Figure 13. Through crack AFGROW results vs lab data.

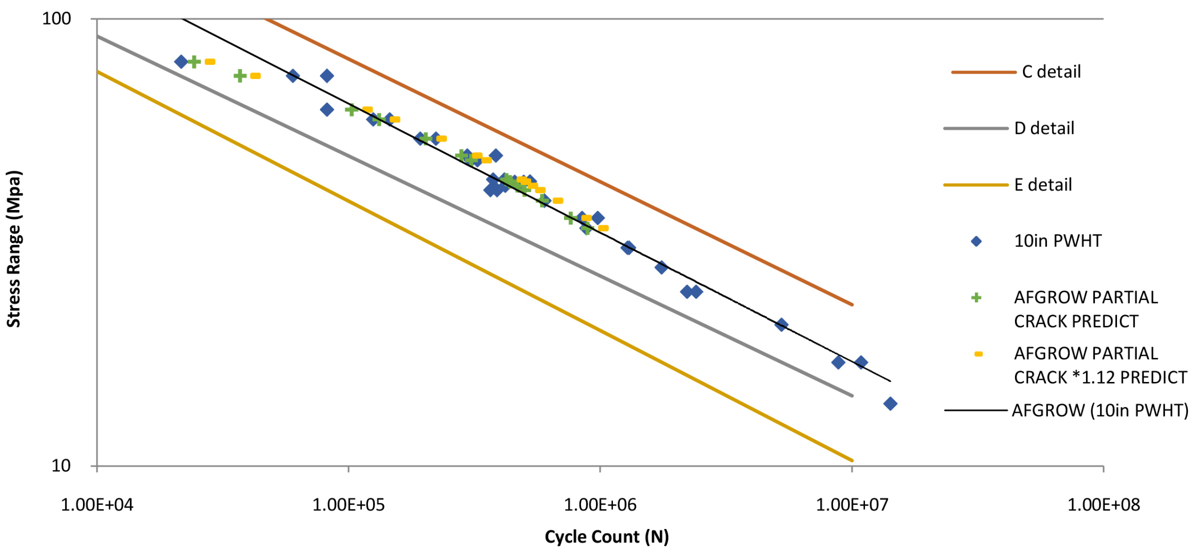

Figure 14. Partial crack AFGROW results vs lab data.

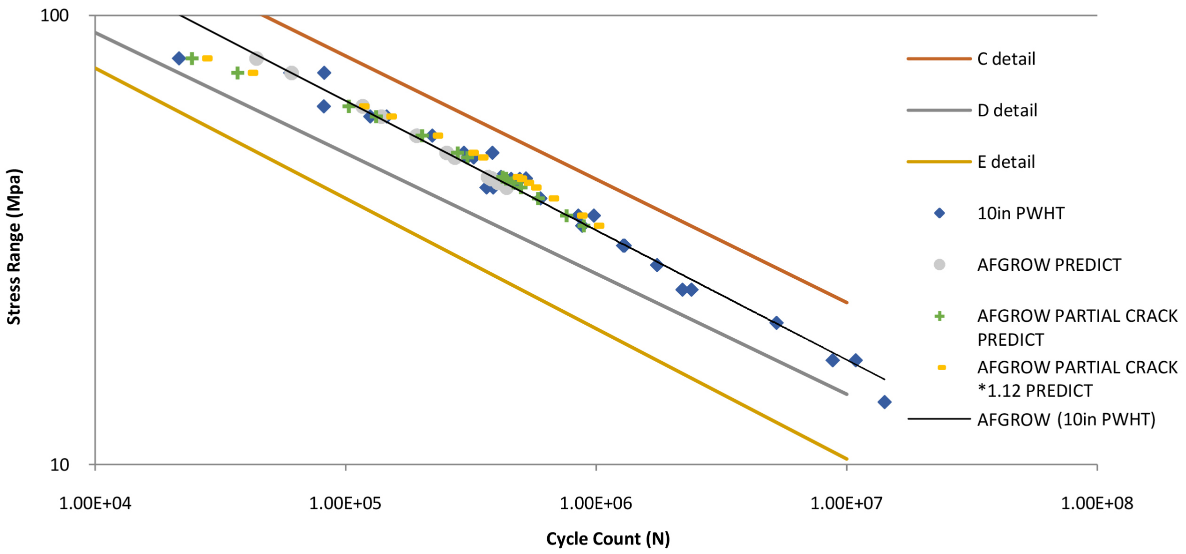

Figure 15. Both plate AFGROW analysis vs lab data.

4. Conclusion

The existing literature exclusively focused on fracture mechanics analysis of notched plates, concentrating on crack growth for the purpose of forecasting fatigue life. Additionally, alternative methodologies such as dynamic analysis, entropy-based approaches and machine learning were employed. The purpose of the present study was to predict the life of aluminum light poles and give a method of approach in such analysis within AFGROW. Initial iteration of the model containing only a partial crack yielded some similarity to laboratory data later in the life of the experiment at lower stress ranges, but at higher stress ranges failed to predict the fatigue life (that being failure occurring at a much shorter cycle range). This prediction led to the beta correction and larger partial opening models Beta corrections had some correlation but fell short in the same manner the partial crack models did. Open hole (crack manipulation) models showed some correlation but showed similar results to the beta correction models. The final iteration of the AFGROW fracture mechanics models (plate) directly correlated to the data obtained from the lab, particularly on the power trendline of the data and occurred in both the through and partial crack models. Models proved that the weld (considered during nominal stress calculation) failed in a manner in which it acts like a plate, initially as a partial crack, then becomes a through crack until catastrophic failure and was proven by how closely the fracture mechanics analysis coincided with the laboratory data. This plate analysis procedure (FEA into AFGROW) can be utilized by engineers in other aluminum light pole scenarios in order to predict fatigue life and can include utilization in the field. Future work utilizing the fracture mechanics plate process could be conducted on different welded connections. This could include welded plates, steel beams in which a weld is present and other structures. Utilization could further prove the validity of the process.

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Data Availability Statement

Cameron Rusnak is to be contacted if such data is requested.

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