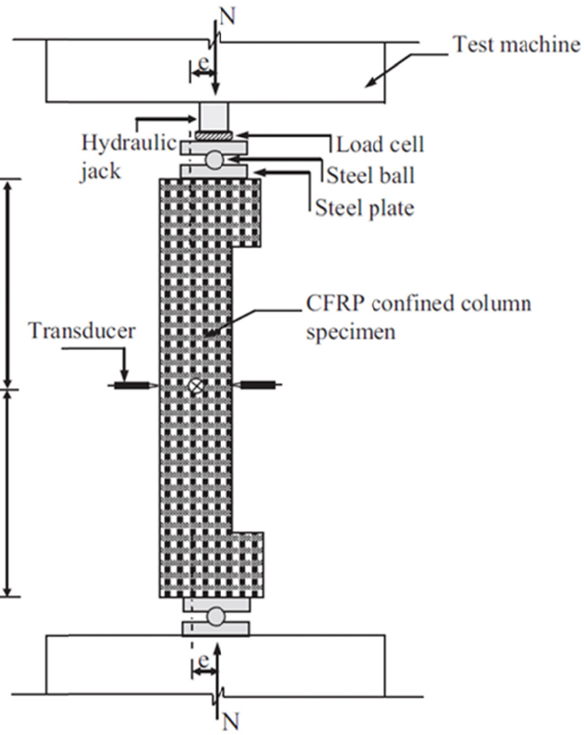

Figure (5): Experiment setup, Figure from (Dundar et al., 2015).

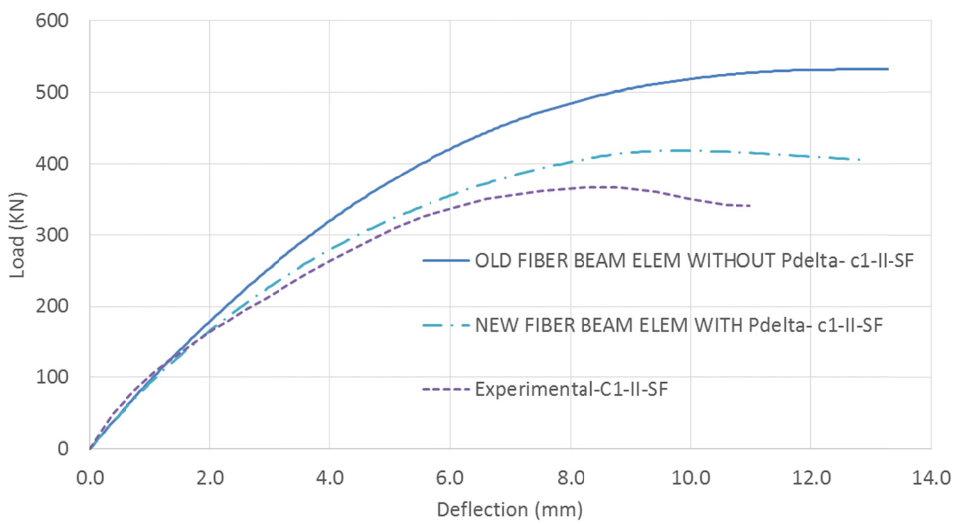

Figure (6): Load-deflection curve for column C1-II-SF tested by (Dundar et al., 2015) and compared with the new and old fiber beam elements.

Conclusion

A new finite element model based on a fiber beam element formulation that considers large displacements was presented. The element uses a displacement-based formulation and considers second order effects. The element can model reinforced concrete members strengthened with steel fibers and carbon fiber sheets under different loading conditions. It was found that the proposed element results are in good agreement with the analytical and experimental results.

References

Alemdar, B. and White, D. (2005). Displacement, Flexibility, and Mixed Beam–Column Finite Element Formulations for Distributed Plasticity Analysis. *Journal of Structural Engineering*, 131(12), pp.1811-1819.

Chan, S. (1988). Geometric and material non-linear analysis of beam-columns and frames using the minimum residual displacement method. *International Journal for Numerical Methods in Engineering*, 26(12), pp.2657-2669.

De Souza, R. (2000). *Force-based finite element for large displacement inelastic analysis of frames*. PhD. University of California, Berkeley.

Dundar, C., Erturkmen, D. and Tokgoz, S. (2015). Studies on carbon fiber polymer confined slender plain and steel fiber reinforced concrete columns. *Engineering Structures*, 102, pp.31-39.

Kang, Y. (1977). *Nonlinear geometric, material and time dependent analysis of reinforced and prestressed concrete frames*. Report No. SESM 77-1. University of California, Berkeley: Division of structural engineering and structural mechanics.

Mullapudi, T. (2010). Seismic analysis of reinforced concrete structures subjected to combined axial, flexure, shear and torsional loads. PhD. University of Houston.

Takayanagi, T. and Schnobrich, W. (1979). Non-linear analysis of coupled wall systems. *Earthquake Engng. Struct. Dyn.*, 7(1), pp.1-22.

Taylor, R.L. (2014). FEAP - Finite Element Analysis Program. University of California, Berkeley. URL: http://www.ce.berkeley/feap

White, D. (1985). *Material and geometric nonlinear analysis of local planar behavior in steel frames using interactive computer graphics*. MS Thesis. Cornell University, Ithaca, N.Y.

Long-Term Fatigue Behavior of Aluminum Shoe Base Details Top Mounted Luminaries

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Abstract

With increased use of welded aluminum light poles along highways and in industrial service applications such as parking lots, harbors, stadiums, etc., it is important that they are sustainable and resist fluctuating wind induced stresses or fatigue loading. Forty-one welded aluminum shoe base light poles were fatigue tested in the structures laboratory of the University of Akron. The fatigue life of the test specimens was considered and used to develop a design S-N curve for the specific shoe base details used on the light poles. The proposed S-N curve derived from the test results, including the endurance limit in high cycle regime, was compared to the Aluminum Design Manual's (2015) category F1.Among forty-one aluminum shoe base light poles, twenty-six specimens failed (63.4%) and the remaining survived (run-outs). Crack development in the specimens was observed on the surface primarily along the weld toe between the tube and cast shoe base. The lower bound S-N curve was extracted and provides approximately 97.5 percent probability of survival for the shoe base detail and is in a good agreement with category F1 of Aluminum Design Manual (2015). Additionally, the run-out data for the fatigue test results, which is taken to be 10 million cycles for the older tests and 20 million cycles for new test group, is in good agreement with the British Standard Institute 8118 and the Aluminum Design Manual (2015). The S-N curve is useful for investigating the fatigue behavior of the light poles during analysis for wind induced loadings.

Keywords: Design; Welded aluminum shoe based light pole; Fatigue test; Fatigue life; High cycle fatigue; Stress range; S-N curve; CAFL.

Introduction

Over the past 20 years, several well publicized failures of welded aluminum light poles due to fatigue crack growth have highlighted the need to better understand the nature of wind loading, the dynamic response of cantilevered pole structures, as well as the fatigue resistance (Caracoglia et al. 2004; Dexter and Johns 1998). Many of these structures are designed for infinite life, and as such, experimental studies of the fatigue behavior in the high cycle regime are necessary. Recent recommendations for the determination of the long-life fatigue response of welded details provides for run-outs at 20,000,000 cycles (AASHTO 2013). A recent study conducted at the University of Akron examined the high-cycle fatigue response of welded aluminum pole to cast shoe base socket connections, the intent of which was to evaluate the Constant Amplitude Fatigue Limit (CAFL). Results of the experimental program are presented, and a proposed S-N curve is discussed.

Background

Several well documented failures of light poles has resulted in research into the understanding of field failures, dynamic behavior under wind and environmental loading as well as the fatigue resistance of welded details common to light poles and traffic signal structures. Fatigue lives of metallic materials were evaluated in the laboratory and predicted analytically by Newman et al. (1999). The computed fatigue lives for the aluminum alloys are in a good agreement with the test data developed under constant amplitude and spectrum loading. Tubular steel lighting columns were fatigue tested by Robertson et al. (2004) and the results compared to closed-form solutions to verify the fatigue damage and life of structures. Hollow circular members of an overhead welded Aluminum sign truss were field tested and were found to be vulnerable to wind induced vibration (Rice, et al. 2008). Resonant vibrations in the members were found to cause fatigue cracking. Roy et al. (2003) studied fatigue life improvements methods for welded transverse stiffeners and cover plate details through testing. Improving the weld profile, increased the fatigue strength. Chang, et al. (2009) attempted to model wind induced loads on high mast poles. Field data were found to be in good agreement with estimated fatigue lives results, and vortex shedding resulting in second mode vibration was observed. A laboratory investigation of the fatigue performance of full penetration groove weld end plate connections was conducted by Roy, et al. (2010) by testing 23 full-scale specimens under constant amplitude loading, and the results compared to the parametric evaluations. It was found that the fatigue limit of the tube to end plate groove welded connections may exceed that as given by Category D of the AASHTO specifications and the geometric parameters have a considerable influence on the fatigue performance of the structural connections. The fatigue resistance and design load capacity of welded aluminum cantilever truss structures subjected to wind loading was field-tested and investigated theoretically by Rice et al. (2012). Structural behavior was evaluated by considering the static and dynamic loading of the field-test results and analyses. The measured stresses in the tests were lower than allowable design stresses. Repetto and Solari (2010) performed a failure analysis of an anemometric pole and antenna tower subjected to wind induced vibrations and fatigue. A procedure outlined provides a means to assess the fatigue life, stress state, damage and also provides insight into the behavior of the structures. Barle, et al. (2011), investigated the fatigue performance of highway sign support structures and concluded that the use of extreme monotonic wind loading in design was not sufficient. In addition to the examination of strength, a fatigue analysis using stress spectra is required. Different design variants for sign support structures were evaluated, and the results were summarized. Caracoglia and Jones (2007) investigated failures of welded aluminum light poles in Illinois during a severe storm. Both analytical models and laboratory tests were conducted, and the most likely causes were attributed to the asymmetric build-up of ice and subsequent galloping of the poles and/or buffeting. Coughlin and Walbridge (2012) conducted constant and variable amplitude fatigue tests on small-scale non-load carrying aluminum fillet welds. A fracture mechanics model was developed, and results of the tests and simulations were used to examine the adequacy of design provisions. Fatigue life of welded aluminum cast shoe base and through plate socket connections were evaluated by laboratory fatigue testing. The fatigue resistance of shoe-base details was superior as compared to the through plate joints (Azzam and Menzemer 2006).

Fatigue Tests

Test Setup

Forty-one cantilevered pole-shoe base specimens were tested in order to investigate the fatigue behavior of the pole to shoe-base connection (Fig. 1).

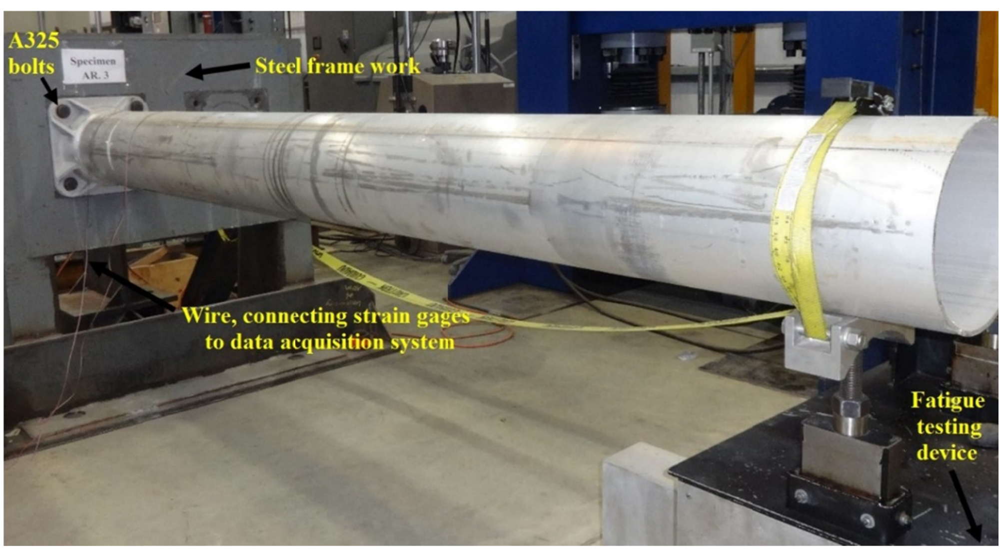

Fig. 1. Shoe base aluminum light pole. (Photograph courtesy of testing engines and structures center, The University of Akron, Akron, OH)

Specimens consisted of 25.4 cm diameter, 0.635 cm thick aluminum extrusions, welded to 356 integrally stiffened cast shoe bases. Each specimen was welded in the T4 temper using 4043 as the filler alloy (Fig. 2). Each sample was Post Weld Heat

Treated (PWHT) for 6 hours at 182°C (360°F) and mechanically straightened. Specimens were rigidly attached to a steel framework using four 1 in. diameter A325 steel bolts. (Fig. 1)

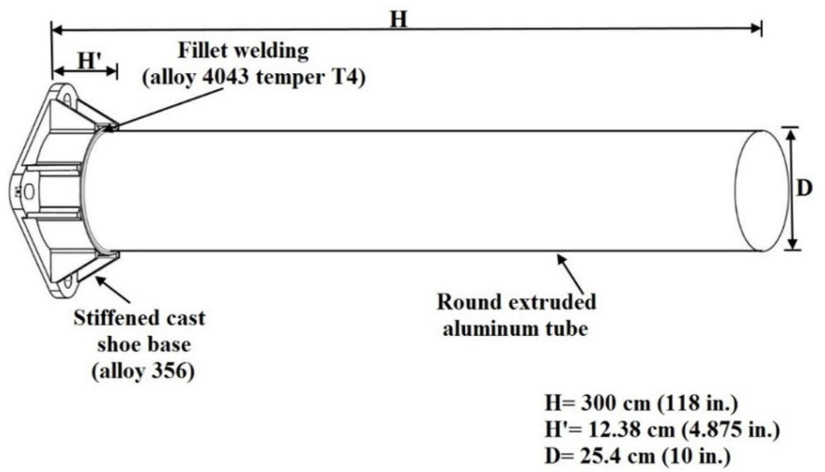

Fig. 2. Shoe base light pole dimensions for fatigue design.

Concentrated Load was applied to the free end of the cantilever and continuously cycled until the specimen failed or 20,000,000 cycles had been applied. The fatigue testing device is displacement controlled and is able to accommodate the testing of two specimens simultaneously (Fig. 3). Initial specimens were tested using a 1 Hz loading frequency. However, this was increased to 2 Hz frequency in order to reduce testing time for the run-out specimens.

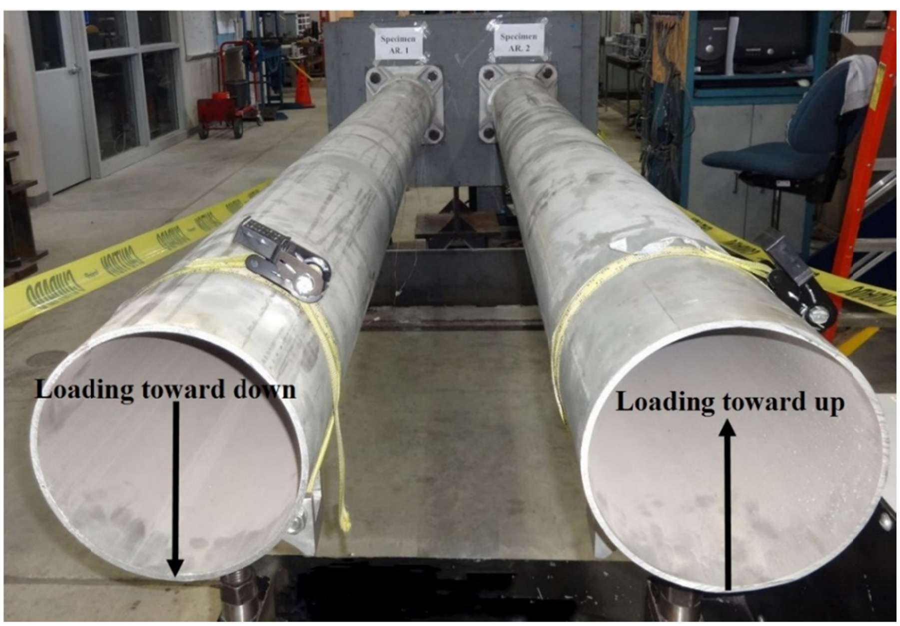

Fig. 3. Fatigue testing device for two specimens together. (Photograph courtesy of testing engines and structures center, The University of Akron, Akron, OH)

Strain gages were installed on the top and bottom surfaces of the tube adjacent to the fillet weld that joins the shoe base casting to the tube. Center of the strain gages were placed within 2-3 times the thickness of the tube away from the weld toe (Fig. 4). The strain gages are directly connected to a data acquisition system through wires.

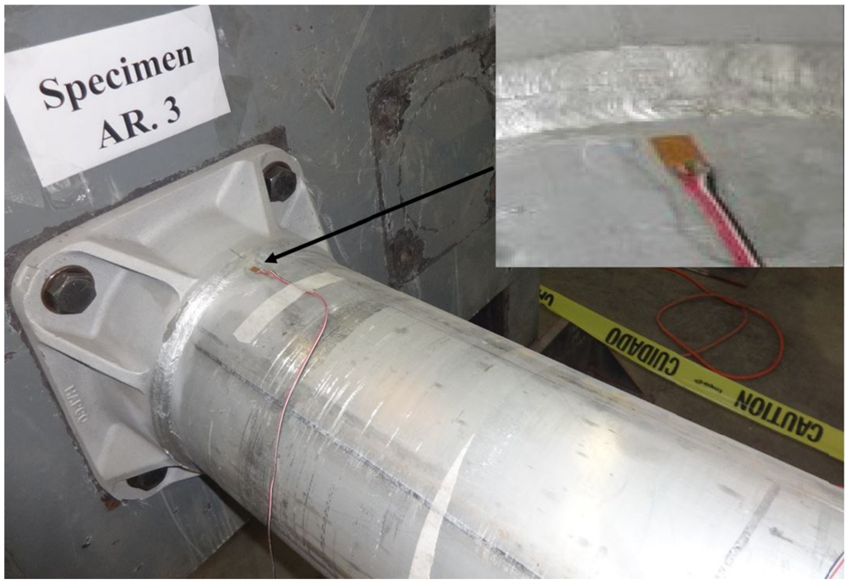

Fig. 4. Position for strain gages. (Photograph courtesy of testing engines and structures center, The University of Akron, Akron, OH)

A Micro Measurements System 8000 connected to a personal computer was used to record the data in short bursts at four hour intervals. Poles were mounted to the rigid steel framework (Fig. 1) and the displacement adjusted until the target strain range was obtained. A modified staircase method was used, beginning with a stress range of 51.7 MPa (7.5 ksi). Each successive test employed a target stress range that was lower by a minimum of 3.45 MPa (0.5 ksi), provided the previous specimen failed before 20,000,000 cycles. This was continued until both specimens mounted in the testing device reached 20,000,000 cycles without failure.

Monitoring

Specimens were visually inspected several times a day, using a 10x hand powered magnifying glass with a light source. Strain levels were examined daily to ensure end levels were being maintained and the considered stress ranges applied to the specimens. Daily observations were maintained in a detailed test log.

Test Results

Fatigue life is generally considered to consist of two steps: crack initiation and crack propagation (Fig. 5). However, crack initiation life for welded structures is virtually non-existent. Eventually sudden fracture for a ductile material like aluminum shoe base details was observed. Fracture mechanics provides the means to assess the fatigue life of welded components and structures. Modelling is being developed as part of the project. Many structures are designed for infinite life through use of the CAFL. Thus, it is necessary that tests be conducted in the long life regime. In some instances, tests conducted in this series required nearly eight months of floor time to complete.

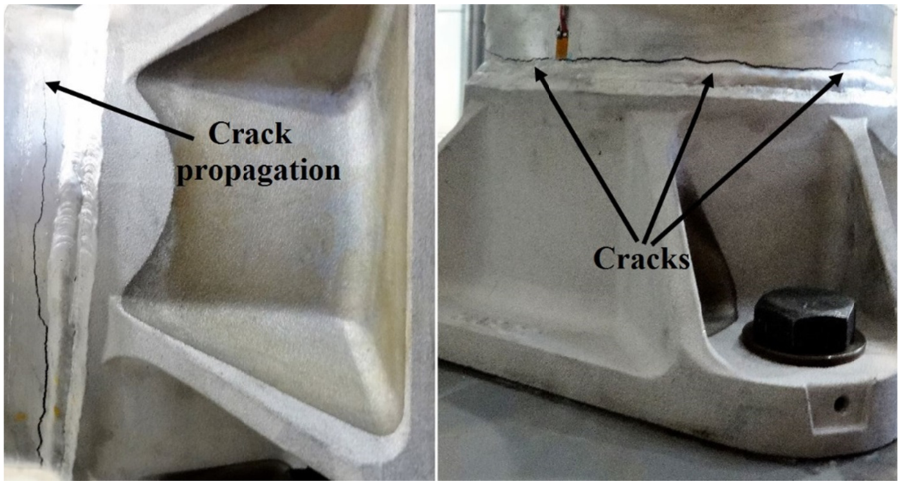

Fig. 5. Crack propagation in the specimens. (Photograph courtesy of testing engines and structures center, The University of Akron, Akron, OH)

Of the 41 aluminum pole samples tested, 26 failed and 15 were run-outs. The resulting failure data is shown in Fig. 6. Fig. 6 depicts the known fatigue data for the welded aluminum pole to shoe base casting details, and includes data developed by Dexter et al. (1998) as well as the University of Akron.

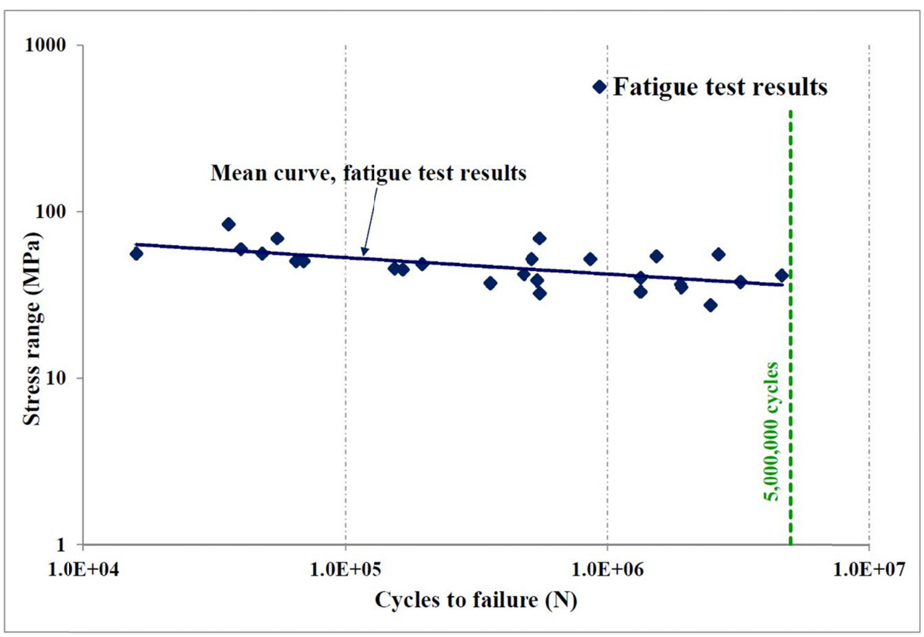

Fig. 6. Failure data for shoe base light poles.

A best fit S-N curve based on failure data is shown in Fig. 6. The mean CAFL, which is estimated to be 33.7 MPa (4.89 ksi), and meets the best fit curve at a cutoff point around 10,000,000 cycles. Equation (1) is defined for the best fit S-N curve.

$$S = 163.5\, N^{-0.098} \qquad (1)$$

Where S is the stress range (MPa), and N the number of cycles to failure.

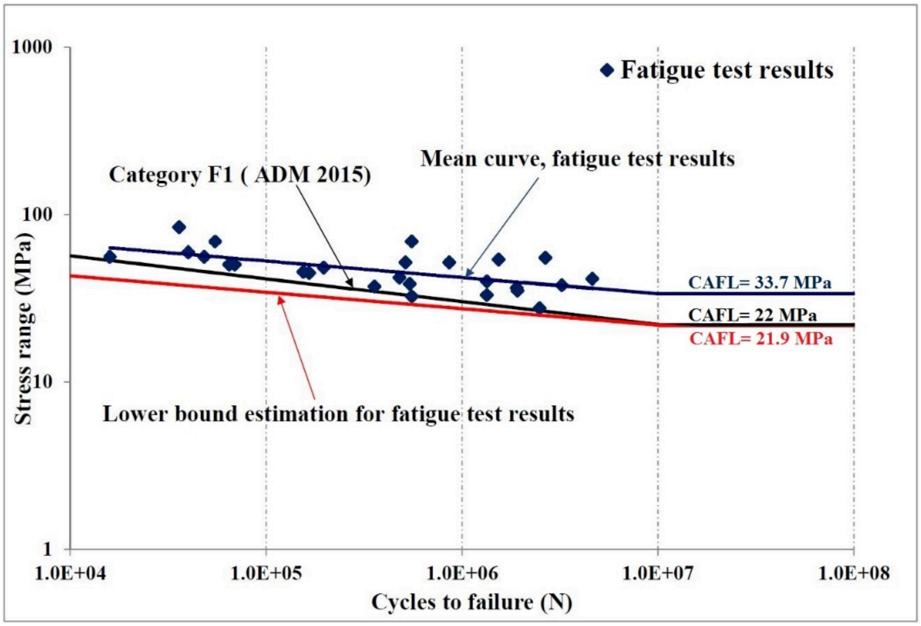

Fig. 7. Combination of best fit, lower bound estimation, and category F1 S-N curve.

Fig. 7 depicts the lower bound that corresponds to a 97.7% probability of survival (Menzemer and Fisher 1993). The lower bound S-N curve (2) for the failed specimens is defined by combination of mean resistance less two standard deviation, using the normal distribution function.

$$S = 106.1\, N^{-0.098} \qquad (2)$$

Where S is the stress range, and N is the number of cycles to failure. The Lower bound S-N curve touches the CAFL at 21.9 MPa (3.18 ksi) for a life of 10,000,000 cycles. Equation (3) shows the category F1 (ADM 2015) and assigned to the shoe base Aluminum poles.

$$S = C_f\, N^{-\frac{1}{m}} \qquad (3)$$

Where C_f and m are constant, and S is the stress range, and N is the number of cycles to failure (Aluminum Association 2015). In the ADM 2015 equation, it is suggested that $C_f = 200Mpa\ (29Ksi)$ and $m = 7.31$. Equation (4) below illustrated for the category F1.

$$S = 200\ N^{-0.137} \quad (4)$$

Results are consistent with the current Category F1 detail as given in the Aluminum Design Manual (ADM 2015) where the CAFL for 10,000,000 cycles is 22 MPa (3.2 ksi), and for the test target life of 20,000,000 cycles, the CAFL is 20.4 MPa (3.0 ksi). The CAFL is consistent with category F1 at 22 MPa where the number of cycles is 10,000,000 cycles (Aluminum Association 2015).

Run-out data for the welded aluminum shoe base details are shown in Fig. 8. Determination of the CAFL from such data is not trivial. During the course of this investigation, a number of tests were conducted in excess of 231 days in order to reach 20,000,000 cycles.

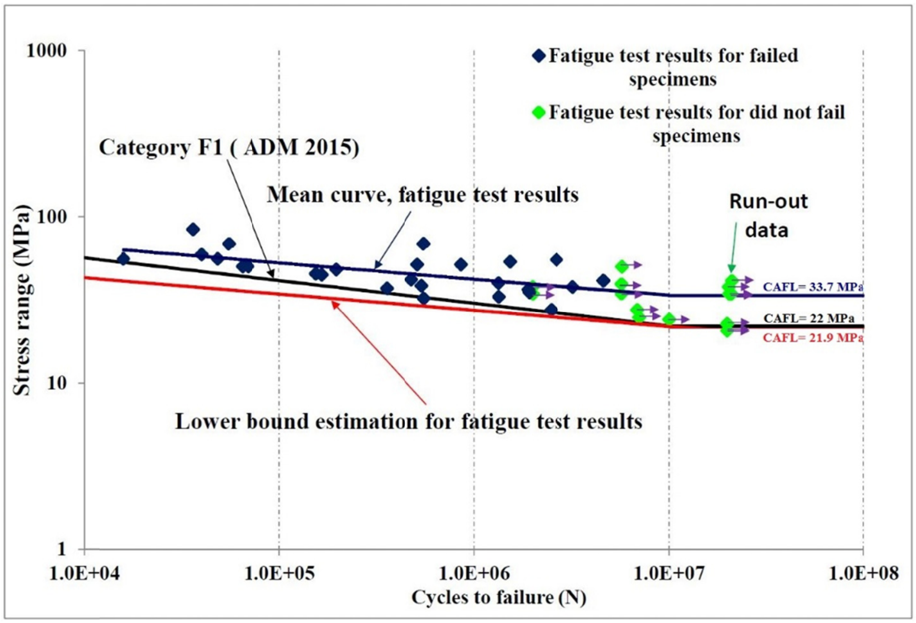

Fig. 8. Fatigue test results shoe base.

Attempts to use advanced statistical techniques to determine a CAFL are often not practical from an engineering design standpoint, as the scatter associated with fatigue data typically increases with cyclic life. Determination of the CAFL is important for structures like light poles given the nature of wind loading that necessitates an infinite life approach.

There has been significant investigation into the endurance limit, or CAFL, or CAFT (constant amplitude fatigue threshold) of structural details in the high cycle regime which provides a distinction between infinite and finite life. The CAFL for the welded shoe base detail currently covered in the Aluminum Design Manual as Category F1, is given as 22 MPa (3.2 ksi) at 10,000,000 cycles. Using the lower bound S-N curve estimate for the welded shoe base data set results in a CAFL of 20.4 MPa (3.0 ksi) at 20,000,000 cycles or 21.9 MPa (3.18 ksi) at 10,000,000 cycles. As shown on Fig. 9, ten tests that were conducted at stress ranges of 34.5 MPa (5 ksi) or lower did not fail after 20,000,000 cycles.

In this paper, the run-out fatigue test results are compared to the other specifications for details consistent with welded aluminum shoe base light poles. For this purpose,