

Multiaxial fatigue life assessment of a vertical-lift bridge connection using strain rosette data

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ABSTRACT: Fatigue-induced damage is one of the most common types of damage experienced by civil engineering structures subjected to cyclic loading such as bridges. The applicability of multiaxial non-proportional fatigue life assessment is shown using strain measurements collected from a welded gussetless truss connection of a vertical-lift bridge. Methods for uniaxial loading and multiaxial non-proportional loading are compared. It is shown that non-proportional loading can cause a significant decrease in the estimates of remaining fatigue life.

Civil structures are subject to different types of cyclic loading such as vehicular, mechanical, and wind loads. Such dynamic effects can cause cyclic loading and unloading with response stresses above a certain endurance limit. Continuous application of this types of stresses may induce microcracking that can eventually propagate and produce failure of the member or the structure. This type of internal damage is known as fatigue and has been found to be cumulative and irreversible. Small stress amplitude cycles that result in elastic deformations lead to longer fatigue life estimates. This type of fatigue is also known as high cycle fatigue (HCF). On the other hand, repeated plastic deformations in each stress cycle are characteristic of low cycle fatigue

(LCF), such as deformations can occur in extreme seismic events.

Fatigue can result in substantial financial losses and structural failures compromising the safety of users. Fatigue research initiated in the early 1800's when Jean-Victor Poncelet studied this phenomenon as a failure mechanism establishing the term fatigue in 1829. Then, W.J.M. Rankine investigated the failure of railway axels in 1843 (Samuel and Weir, 1999). In 1858, quantification of fatigue lifetimes was introduced by August Wöhler (Wohler 1858). His work resulted in the now widely used S-N curves where S is the uniaxial stress level that a material can withstand, and N is the number of cycles. These S-N curves are developed under cyclic axial loading tests. Therefore, directly applicable when a structural

component subjected to uniaxial stresses is assessed for remaining fatigue life.

Welded connections are generally more susceptible to fatigue cracking compared to bolted connections. Factors such as weld defects, residual stresses, discontinuities, and lack of fusion can reduce the fatigue life of a connection (Haghani, Al-Emrani, and Heshmati, 2012). Guidelines and provisions for fatigue evaluation of welded structures are available in the American Association of State Highway and Transportation Officials (AASHTO 2018b) specifications for highway bridges, the federal highway administration (FHWA 2015), the American Railway Engineering and Maintenance-of-way Association specifications for rail bridges (AREMA 2016), the American Society for Testing and Materials design and evaluation standards (ASTM 2000), and the German Institute for Standardizations (DIN in German) DIN4112. In general, these specifications suggest the estimation of stress ranges using a combination of loads and distribution factors. The resultant stress range is then used in combination with S-N curves to estimate fatigue strength. However, these uniaxial fatigue evaluation methods are in many cases insufficient for large in service structures with complex geometry and connections subjected to multiaxial, non-proportional loadings. Multiaxial loading is common in structures with complex geometries and independently varying loadings such as bridges, machines, aircrafts, and rollercoasters. Such structures can have multidirectional transfer of forces subjecting components to multiaxial stresses. Multiaxial loading can be proportional (or in phase) or non-proportional (out-of-phase). The direction of principal stresses or strains remains constant with respect to the direction of cyclic loading in proportional multiaxial loading while the principal axes directions change over time for non-proportional loading.

A method for fatigue life prognosis and fatigue life prediction for complex structures such as lift

bridges is presented. The method proposed was initially evaluated in a rollercoaster connection (Puerto-Tchemodanova et al., 2019). The critical plane method is used for the estimation of remaining fatigue life using strain rosette data. Strains collected from strain rosettes in a gussetless truss bridge connection are used to determine the critical plane orientation using Findley's criteria (Findley 1958). The critical plane is defined as the plane that represent the most damaging fatigue orientation leading to the least fatigue life (Bannantine and Socie, 1992). This approach consists of examining the detailed stress and strain states on all potential critical planes of a component based on a previously determined fatigue criterion. Stresses at the critical plane location are used for estimation of the number of stress reversals induced by live loads and the number of associated cycles using the rain-flow method (Socie 1993). Uniaxial and multiaxial fatigue analysis methods proposed for non-proportional loading are compared. The critical plane method is used for the estimation of multiaxial fatigue life and compared to procedures used in the current AASHTO's manual for bridge evaluation. It is shown that non-proportional loading and the location of the critical plane can result in a significant decrease in the estimates of remaining high cycle fatigue life. Therefore, current methodologies used in complex geometries and based on uniaxial stresses for the estimation of fatigue life can overestimate the fatigue strength or life of a member. The methodology proposed in this research is anticipated to be used for real-time fatigue prognosis and evaluation tools for bridge networks.

MEMORIAL BRIDGE FATIGUE LIFE ANALYSIS

The original World War I Memorial Bridge was located between the Badger Island and Kittery, Maine and Portsmouth, New Hampshire, over the Piscataqua river. It was built between 1920 and 1923. Due to structural deficiency, the bridge was closed to traffic and demolished in

2012. A replacement bridge was constructed re-using the original piers. The new Memorial Bridge, opened in 2013, is a truss bridge with unique gussetless connections and a vertical lift. Aiming to reduce construction time and improve long-term maintenance and inspection requirements, the gussetless connection provides a smooth transfer of forces between diagonal and chord members. These connections use cold-bent steel plates as flanges for transition from one member to other members. Figure 1 shows an instrumented connection at the lower cord of the new Memorial bridge.

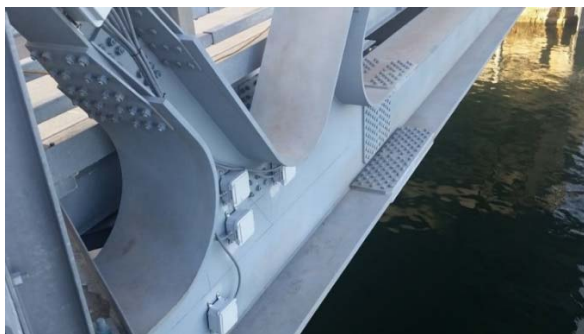


Figure 1 Memorial Bridge gussetless connection at Lower cord of south span (picture taken from: <https://livingbridge.unh.edu/bridge/>)

The south horizontal span and vertical lift tower of the bridge is currently instrumented. Data collections started in 2016 as part of the living bridge project lead by researchers the University of New Hampshire (UNH) and sponsored by the National Science foundation (NSF), New Hampshire department of transportation (NHDOT), FHWA and the United States department of energy (DOE) (Mashayekhizadeh, Santini-Bell, and Adams, 2017). The sensing network proposed in this project consists of structural response sensors underwater instrumentation and cameras, and weather stations. Monitoring instrumentation to capture structural response include weldable rosette strain gages, uniaxial strain gages, uniaxial accelerometers, and biaxial tiltmeters. Rosette strain gages were installed using a capacitive discharge spot welded and covered

with zinc spray coating after installation. Two connections of the horizontal span and vertical tower of the bridge along the east face of the south span were instrumented. However, for examination and demonstration of multiaxial fatigue analysis method, data collected only from strain rosette SG-5-E-R-E, as shown in Figure 2, will be used. This rosette is located between two diagonal members in a lower cord connection. Figure 2 shows the instrumentation placed in this connection.

Data collected from strain rosettes was sampled at 50 Hz. Raw data was baseline corrected to zero microstrain measurements.

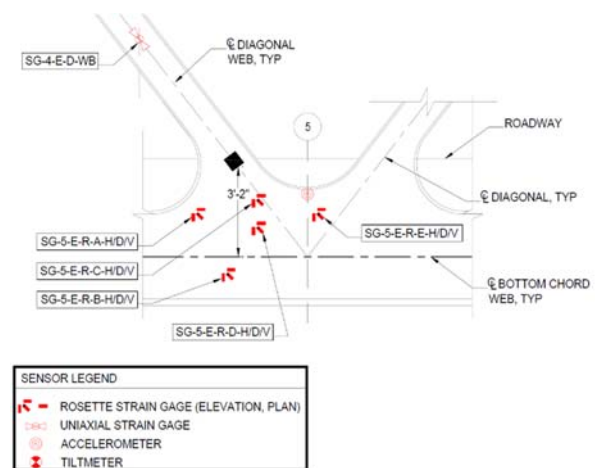


Figure 2 Memorial bridge sensors at lower cord connection of east face of the south span

This process accounts for any drifts in measurements that might distort fatigue life predictions. In addition, a finite input response (FIR) band-pass filter was designed to filter frequencies below 0.005Hz and above 10Hz. Analysis of the data in frequency domain showed that this range contained the most representative frequencies. Figure 3 shows a 200 second sample of the filtered and unfiltered data collected. In general, recorded strains are quite low and do not exceed ± 5 microstrains. Peaks seen thought the time line represent traffic events.

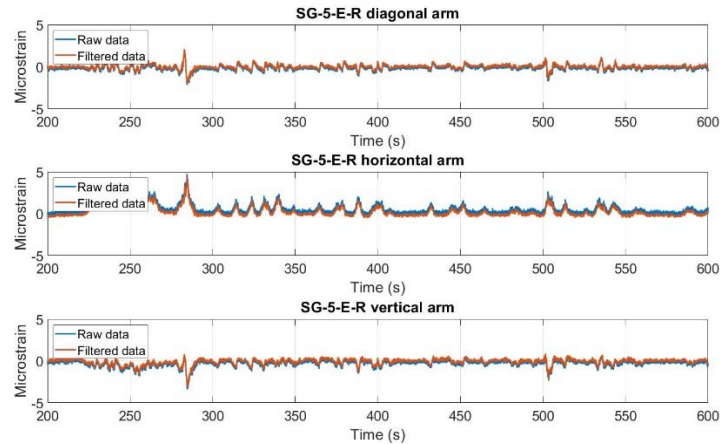


Figure 3 Memorial bridge SG-5-E-R-E measured strains

FATIGUE LIFE PROCEDURES AND PREDICTIONS

- Fatigue damage occurs when a large number of loading and unloading cycles occur in a member or connection. Fatigue in metals is defined as the process of initiation and growth of cracks under the action of repetitive tensile loading cycles (FHWA 2015). Fatigue cracking became a concern in the bridge community since the 1950s when welding was the preferred method for the fabrication of steel bridges replacing the use of rivets and bolts in connections. Due to possible welding defects stress concentrations are more likely to occur inducing microcracking and eventually leading to fatigue cracks. In addition, welding facilitates crack propagation from one member to another. AASHTO guide for fatigue evaluation of existing bridges recommends procedures for the estimation of remaining fatigue life of bridge components using strain data (AASHTO 2018b).

This procedure includes: the identification of locations within the connection with high concentration of tensile stresses, installation of strain gauges and data collection at these locations, stress or strain data cycle counting using Miner's rule, and estimation of remaining fatigue (Alampalli and Lund 2006). This last step involves the use of S-N curves mainly

based on the geometry of the connection. S-N curves relate the number of cycles to failure at different stress ranges. There are currently eight different categories provided by AASHTO to which bridge components and details can be classified. Detail category C shown in Figure 4 is given as an example of the available categories.

However, inservice loads can cause a combination of bending, torsional and axial stresses in a connection. Various combinations of these stresses can cause multiaxial effects that might decrease the fatigue life of a connection. If the orientation of the principal stresses due to this combined loading remains constant in time, the load history is said to be proportional. On the other hand, if principal stresses vary in time the load history is said to be non-proportional.

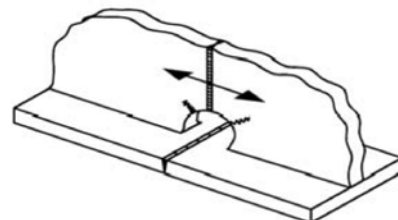


Figure 4 Detail Category C. Rolled cross sections with weld access holes. Table 6.6.1.2.3-1 (AASHTO 2018b).

Multiaxial loading have been studied since the 1950s when first methodologies to estimate the fatigue life of components subjected to multiaxial loading were published (Findley, 1958, Sines, 1959, McDiarmid, 1991). This early work focused mainly on materials with negligible plastic strain or material that will experience high cycle fatigue. Since then several approaches have been developed to determine the effects of multiaxial loading on the estimation of remaining fatigue life. However, a common methodology for the estimation of fatigue life under multiaxial stresses has not been accepted yet by the practicing community. The large amount of publications and experimental data generated since the 1950s is significant and have advanced in the understanding of multiaxial fatigue analysis. However, accurate and reliable evaluation of multiaxial fatigue design, life estimation, and failure assessment is still challenging for the research community.

Stress-based models are widely used when structural components operate under stress levels that limit deformations to the elastic region of the material or in other words under high cycle stresses. The research presented here assumes that the material is ductile-behaving and subject to high cycle stresses therefore plastic deformation is neglected. Successful stress-based multiaxial criteria consider a shear and normal stress component (Socie 1993). In ductile materials such as steel, cracks nucleate and grow on preferable planes rather than at random orientations (Fatemi and Shamsaei, 2011). Furthermore, the orientation of the crack growth does not vary as the number of cycles increases. In ductile materials, this observation along with the remark that microcrack growth occurs in the presence of

shear stresses and that normal stress will affect the opening of a crack provided the physical basis for critical plane approaches to multiaxial fatigue. Tensile normal stresses will cause the crack to open therefore reducing the fatigue life of a component while compressive normal stress will cause the crack to close, resulting in higher fatigue life estimations.

Yield criteria based on principal stresses and Von Mises stresses are typically used for multiaxial fatigue life estimations. However, when a component is subjected to out-of-phase or non-proportional loading these criteria can underestimate fatigue life (Shamsaei and Fatemi, 2009). In situations when principal stresses vary in magnitude and direction over time, multiaxial fatigue damage has been correctly estimated when a critical plane is first localized (Chu, Conle, and Bonnen, 1993). The critical plane is defined as the plane direction that causes the most damaging fatigue life. This approach consists on examining the detailed stress and strain states on all potential critical planes of a component based on a previously determined fatigue criterion. The critical plane approach has been found to be applicable to components subjected to both non-proportional and proportional loadings (J. Li, Zhang, Sun, and Li, 2011). In addition, it can be applied to different types of material besides steels such as elastomeric materials (Mars and Fatemi, 2005).

Figure 5 shows the variation of the principal stress orientation over 100 seconds for strains collected in rosette SG-5-E-R-E. Magnitude and orientations of principal stresses show significant variation over time. This figure demonstrates that multiaxial non-proportional effects should be considered for this connection when estimating remaining fatigue life.

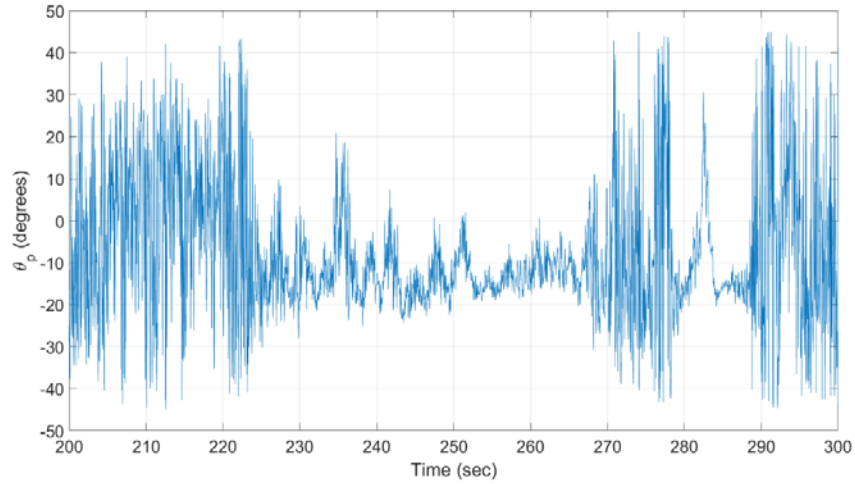


Figure 5 Variation of principal stress orientation over time at SG-5-E-R-E on the Memorial Bridge

Furthermore, Figure 6 compares shear and normal strains at rosette SG-5-E-R-E based on research by Meggiolaro, et al. (2009). For proportional loading this comparison will result in a linear relationship. However, the strains experienced by the Memorial bridge at this lower cord connection shown to be randomly out of phase, indicating independently applied live loads. Therefore, to determine the multiaxial fatigue life a critical plane is first located to determine orientation of the most critical fatigue prone plane. In addition, for comparison purpose, remaining fatigue life is calculated using uniaxially based procedures suggested by the AASHTO's manual for bridge evaluation.

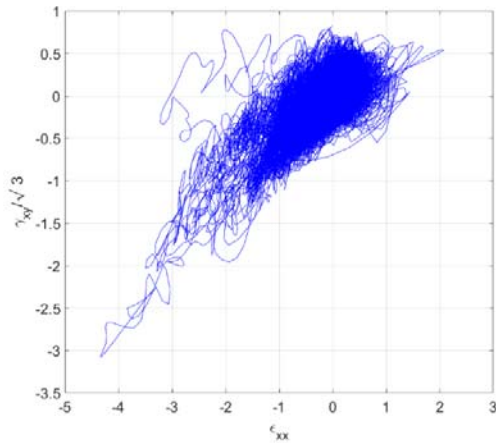


Figure 6 Non-proportional evaluation. Normal versus shear strains of SG-5-E-R-E at the Memorial Bridge

Uniaxial fatigue life calculations -

Evaluation of bridge fatigue life is usually performed using a single strain gage. Usually, direction of tensile stresses is first identified in the member or component then strain gages are placed in this orientation (Saber et al. 2016, Zhou, 2006, Alampalli and Lund, 2006). However, in more complex details or connections such as the connection shown in Figure 2 the change in the cross-section of the lower cord and diagonal elements can cause complex state of stresses.

In this type of connections strain rosettes will give a better understanding of the distribution of stresses in complex geometries. When strain rosettes are used, fatigue life estimation are usually based on cycle counting of principal stresses or Von Mises' stresses (Mcgeehan, et al., 2019, Baldwin and Thacker, 1995).

According to AASHTO's manual for bridge evaluation field measurements of strains represent the most accurate mean to estimate the effective stress ranges at fatigue-prone details. The remaining life of a fatigue prone detail in years is given by the equation (AASHTO 2018a)

$$Y_{REM} = \frac{\log\left(\left(\frac{N_{av}-N_1}{365n[(ADTT)_{SL}]_{PRESENT}}\right)\left(\frac{g}{1+g}\right)+1\right)}{\log(1+g)} \quad (1)$$

where,

N_{av} : Number of initially available stress cycles. Given by the equation:

$$N_{av} = \frac{R_R A}{(\Delta f_{eff})^3} \quad (2)$$

R_R : Resistance factor specified for evaluation. For this connection it is assumed to be 2.1. Mean life for the new Memorial Bridge was calculated for detail category C per Table 6.6.1.2.5-1.

A : Detail Category constant. Assumed to be $44 \times 10^8 \text{ ksi}^3$ per Table 6.6.1.2.5-1

N_1 : Number of stress cycles consumed over the present age. Since the Memorial bridge was recently opened, this variable is assumed to be zero.

g : Traffic volume growth rate. Assumed to be 2%.

n : Number of stress-range cycles per truck passage. Taken as 1.0 per table 6.6.1.2.5-2.

$[ADTT_{SL}]_{PRESENT}$: Present average number of trucks per day in a single lane. The average annual daily traffic (AADT) in 2015 at the memorial bridge was 7900 according to NHDOT (NHDOT 2015). Assuming a 2% growth rate. The $[ADTT_{SL}]_{PRESENT}$ is calculated to be 1817.

Δf_{eff} : Effective stress range estimated through field measurements using the following equation based on the linear damage rule also known as the Palmgren-Miner rule (Miner 1945),

$$\Delta f_{eff} = R_s \left(\sum \gamma_i \Delta f_i^3 \right)^{\frac{1}{3}} \quad (3)$$

where,

R_s : Stress-range estimate partial load factor = 0.85

γ_i : Percentage of cycles at a particular stress range

Δf_i : Measured stress range histogram of magnitude greater than one half of the constant amplitude fatigue threshold of the fatigue prone detail. For the purpose of this study all stress ranges will be counted for the calculation of the remaining fatigue life.

Principal stresses were calculated to determine the number of cycles and stress range. The rain flow counting algorithm was used to determine the number of cycles at each range of stress (ASTM, 1985). Figure 7 shows a histogram of the number of cycles and stress amplitudes of principal stresses during 1380 seconds calculated from in service measured strains.

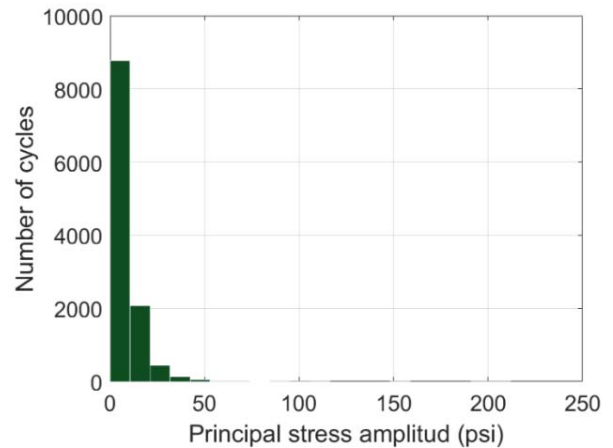


Figure 7 Histogram of principal stresses at SG-5-E-R-E at the Memorial Bridge

During a period of approximately 20 minutes, cycle counting of principal stresses show that most stress amplitudes experienced by the connection are lower than 50 psi. Using Eq. (3) effective stresses are 15.2 psi and $N_{av} = 2.63 \times 10^{15}$. Based on these values a total of 917 years or infinite life is estimated as the remaining fatigue life using Eq. (1). This is considered an infinite life for the connection shown in Figure 1 at the strain rosette SG-5-E-R-E shown in Figure 2. Furthermore, it is clear

that 20 minutes is a very short time to use for fatigue life estimation, however, this setup is simply for comparison of fatigue life predictions using uniaxial and multiaxial methods.

Multiaxial fatigue analysis - Stress-based critical plane models, such as Findley's model, has shown to work well for high cycle fatigue, where plastic deformation can be neglected (Bruun and Härkegard, 2015). The cumulative effect of fatigue is calculated using Eq. (3) which assumes linear accumulation of stresses. Although other theories have been proposed such as the double linear damage model by Mason and Halford (Manson and Halford, 1981), the linear damage rule is the most commonly used damage accumulation method used in multiaxial fatigue analysis (B. Li and de Freitas, 2002; Macha and Niesłony, 2012; Sonsino, 2009). Variable amplitude cycles are common when service loads are measured in structures. In order to determine the different stress cycles within the data collected a rain-flow counting algorithm is used in the shear stress history at the orientation of the critical plane (Bannantine and Socie, 1992).

Stress-based multiaxial damage parameters shown to be effective include shear (τ) and normal stresses (σ_n) and have the following form,

$$\Delta\tau + k\sigma_n \quad (4)$$

Findley's parameter is used to determine the location of the critical plane. Findley proposed a linear combination of shear stresses and the maximum normal stress. The maximum value of the combination of cyclic shear stress amplitudes and maximum normal stress determines the location of the critical plane (Findley 1958). The critical plane is assumed to be the plane most likely to experience the highest fatigue damage.

$$\left(\frac{\Delta\tau}{2} + k\sigma_{n,max}\right)_{MAX} = f \quad (5)$$

Where, the constant k is the material coefficient. This constant is found to be

between 0.2 and 0.3 for ductile materials (Bruun and Härkegard, 2015). Findley's criterion is combined with Basquin's stress life relationship to estimate remaining fatigue life (Socie and Marquis, 2001)

$$\left(\frac{\Delta\tau}{2} + k\sigma_{n,max}\right)_{MAX} = \tau_f^*(N_f)^b \quad (6)$$

where,

$$\tau_f^* = \tau_f' \sqrt{1 + k^2} \quad (7)$$

where τ_f' is torsional fatigue strength, b the fatigue exponent, and N_f the number of cycles to fatigue failure of the material in uniaxial testing. The right side of Eq. (6) corresponds to the elastic part of the S-N curve. The number of stress cycles within the data collected is determined using a rain-flow counting algorithm in the shear stress history at the orientation of the critical plane. The critical plane is assumed to be the largest value of the damage parameter $\frac{\Delta\tau}{2} + k\sigma_{n,max}$ at different orientations. Figure 8 shows the change of shear stress amplitude and Findley's damage parameter over different plane orientations. Zero degrees orientation corresponds to the original orientation of the strain rosette SG-5-E-R-E.

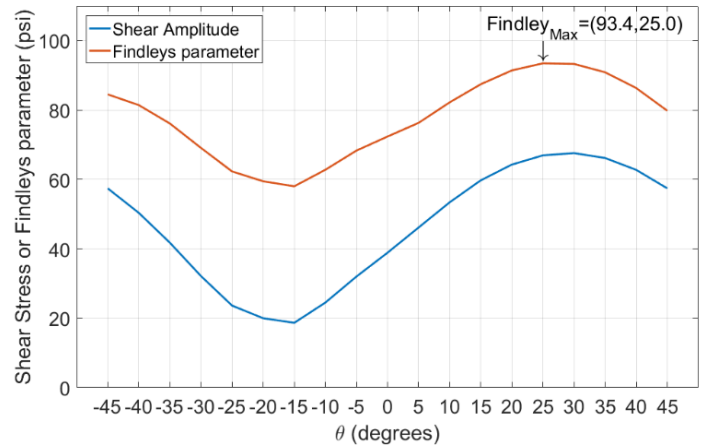


Figure 8 Critical plane directions using Findley's damage parameter at orientations between -45 and 45 degrees.

The maximum value of the Findley's parameter is found at 25 degrees. This orientation is assumed to be the most damaging fatigue plane or the critical plane orientation. The rain flow counting algorithm is used to count shear stress cycles at 25 degrees. For every cycle counted Findley's parameter is also calculated based on the amplitude and maximum normal stress at each cycle. Figure 9 shows a histogram of the resultant amplitudes of the Findley's parameter.

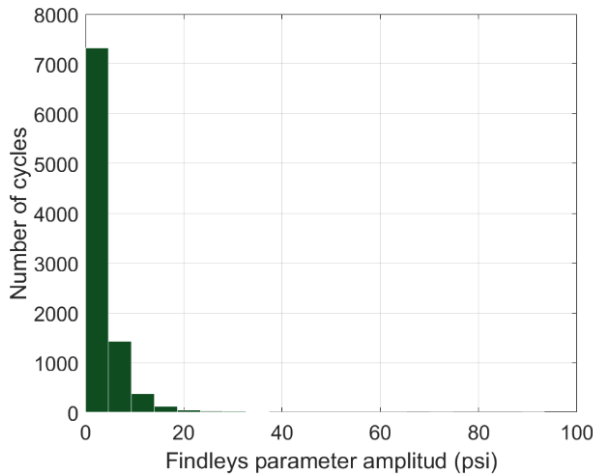


Figure 9 Histogram of Findley's parameter at the critical plane orientation

Magnitude of Findley's parameter found for each shear stress cycle are mostly below 20 Psi. Although, amplitudes shown in Figure 9 are lower to principal stress amplitudes shown in Figure 7 fatigue life estimates are lower. When combination of forces such as tension and, flexure and torsion is present fatigue life can be significantly reduced. Since S-N curves given in AASHTO's manual for bridge evaluation are based on uniaxial testing procedures, a different detail category constant (variable A in Eq. (2)) will be used. Constant A for non-proportional multiaxial fatigue estimates, is inferred from the S-N curve of a laboratory specimen tested under axial-torsion and biaxial-tension for a steel with yield strength of 50 ksi (Kurath and Fatemi, 2009). Using $\tau'_f = 73.2 \text{ Ksi}$ and $k = 0.3$ from Eq. (7), constant A is

calculated to be $4.47 \times 10^5 \text{ Ksi}^3$ (Lee, Abbas, and Ramey, 2010). Effective stresses are calculated using Findley's parameter amplitude and Eq. (3). Then, using $\Delta f_{eff} = 6.68 \text{ psi}$ and $N_{av} = 3.15 \times 10^{12}$ a total of 577 years is estimated as remaining fatigue life. Again, this is considered an infinite life using the multiaxial fatigue life calculation. However, the years of remaining fatigue life estimated are less than the years calculated using uniaxial fatigue procedures.

CONCLUSIONS

Given a unique truss connection at the Memorial Bridge, remaining fatigue life is estimated using two different procedures. Uniaxial based procedures recommended by AASHTO's manual for bridge evaluation and multiaxial procedures using the critical plane method. As expected, both methodologies resulted in infinite life estimations. However, when the critical plane method is used the total number of estimated remaining fatigue years is approximately 40% lower than estimated remaining fatigue years using AASHTO equations. Therefore, it is concluded that:

- Commonly used uniaxial fatigue analysis methods are insufficient in complex structures that experience variable amplitude, multiaxial, and non-proportional loading.
- Critical plane method resulted in a lower fatigue life estimate compared to uniaxial estimate for the connection studied.
- Multiaxial stresses present in complex connections can reduce the fatigue life. Therefore, generalized S-N curves based on uniaxial estimates shall not be used when multiaxial non-proportional stresses are present.
- Non-proportional loading and the accuracy of the critical plane estimation can result in

a significant decrease in the estimates of remaining fatigue life.

- Fatigue life predictions are often based on measurements taken near a weld line. However, further research is still needed to determine reliable estimates of stress concentration factors and the effect of multiaxial stresses at the weld.
- The methodology proposed is anticipated to be used for real-time fatigue prognosis aiming to address critical needs related to maintenance procedures of complex structures, visual inspection techniques, and evaluation tools for infrastructure networks.

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