What rollercoasters can teach us about fatigue life of bridge connections

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ABSTRACT
Rollercoasters are challenging structures. Although the ever-changing geometry can guarantee a thrilling ride, the complexity of loading patterns due to the intricate geometry make testing and analysis of these structures challenging. Fatigue-induced damage is one of the most common types of damage experienced by civil engineering structures subjected to cyclic loading such as bridges and rollercoasters. Fatigue cracking eventually occurs when structures undergo a certain number of loading and unloading recurrences. This cyclic loading under stresses above a certain limit induces microcracking that can eventually propagate into failure of a member or connection. Because of the geometric and structural similarities between rollercoasters and bridge connections, similar techniques can be used for structural health monitoring and estimation of remaining fatigue life. Uniaxial fatigue analysis methods are widely used for the analysis of bridge connections. However, there is little guidance for the analysis of complex connections. They can experience variable amplitude, multiaxial, and non-proportional loading. In such cases uniaxial fatigue methods are insufficient and can lead to underestimates. A framework for the understanding and analysis of multiaxial fatigue damage using strain data collected from strain rosettes is presented. Uniaxial and multiaxial fatigue analysis methods proposed for non-proportional loading are compared. Methods proposed are applicable to both rollercoaster and bridge connections. The critical plane method is used for the estimation of multiaxial fatigue life. Results show that non-proportional loading and the accuracy of the critical plane estimation can cause a significant decrease in the estimates of remaining fatigue life. This methodology is anticipated to be used for real-time fatigue prognosis and evaluation tools for bridge networks.

Keywords: fatigue life assessment, complex connections, in-service loading, non-proportional loading, multiaxial stresses, strain rosettes measurements, rollercoaster connections, bridge connections

INTRODUCTION

Cyclic loading occurs in civil structures under in-service loading such as rollercoaster and bridges. Loading and unloading effects in such structures and its components can be due to the passage of vehicles, wind loadings, and movement of mechanical parts. Continuous application of this types of loads may induce microcracking that can eventually propagate and produce failure of structural components. This type of damage is known as fatigue and has been found to be cumulative and irreversible.

Fatigue damage can be classified into two categories based on the type of deformations experienced by a structure. High cycle fatigue (HCF) occurs when low stress amplitude cycles result in elastic deformations leading to longer fatigue life estimates. On the other hand, repeated plastic deformations in each stress cycle are characteristic of low cycle fatigue (LCF), such deformations can occur in extreme seismic events or high winds. In service structures normally experience HCF and are designed to never undergo fatigue failure throughout their life or in other words to have infinite fatigue life. However, fatigue cracking is still notorious during the lifetime of common civil structures as rollercoasters and bridges.

Fatigue damage can be quantified with S-N curves. These curves were first introduced by August Wöhler [1] and directly relate the number of cycles a material or connections can withstand under stress cycles at a given amplitude. These S-N curves were developed under cyclic uniaxial loading tests. Subsequently, they can be used to asses remaining fatigue life of structural components in which stresses in one direction are evident or predominant.

In-service loads can cause a combination of bending, torsional, and axial stresses in a connection. Multiaxial behavior of stresses occurs when combinations of these stresses take place. If the orientation of the principal stresses due to this combined loading remains constant in time, the loading history is characterized as proportional. Contrarily, if the orientation of principal stresses varies through time, the connection or structural component experiences non-proportional multiaxial loading. Multiaxial effects are known to significantly reduce fatigue life of a member or a connection [2].

Based on physical observation of the initiation and orientation of fatigue cracks under multiaxial loading, Findley formulated a model that combine the interaction of normal and shear stresses acting on the maximum shear stress plane [3]. Using Findley's criterium, a critical plane can be defined. This plane is defined as the most damaging fatigue orientation leading to the least fatigue life [4]. The critical plane approach consists of examining the detailed stress and strain states on all potential critical planes of a structural component. 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 [5].

In this study, a method for fatigue life assessment of complex connections is presented. The proposed method was initially evaluated for a rollercoaster connection. A connection was instrumented with strain rosettes to compute estimates of remaining fatigue life. Strain histories collected suggest multiaxial non-proportional behavior. Therefore, uniaxial fatigue methods are insufficient to reliability determine remaining fatigue life. A more realistic approach is considered to better represent the interaction of loads in the connection. The critical plane method is used for the estimation of remaining fatigue life using strain rosette data. Given that bridge connections also experience multiaxial interaction of stresses, the methodology proposed is similarly applied to a bridge connection. Uniaxial and multiaxial fatigue analysis methods are compared for the instrumented connections. Remining fatigue life estimates show that non-proportional loading can result in a decrease in the estimates of remaining high cycle fatigue life. Therefore, current methodologies used in complex connections that are based on uniaxial stresses for the estimation of fatigue life can overestimate the fatigue life of a connection.

TESTING

Rollercoaster case study

Roller coaster structures are by nature systems that undergo continuous cyclic loading. Therefore, fatigue cracking is commonly identified by inspectors in these types of structures. Current design and evaluation standards such as the American Society for Testing and Materials (ASTM) committee F24 and the German Institute for Standardization (DIN in German) DIN4112 recommends procedures for the estimation of fatigue stresses of welded steel structures [6]. However due to the complex geometry of these structures, estimation of live loads on the structure becomes cumbersome requiring many simplifications. A more realistic estimate of the remaining fatigue damage of a structure can be obtained by measuring the stress levels that the structure undergoes due to different load patterns.

For a rollercoaster structure in the US, an instrumentation system including sensors, using battery powered wireless data acquisition unit, is used to measure the structure's response to moving loads. A portable, battery-powered DAQ system was used for the collection of data. Strain rosette gages using quarter arm bridges, accelerometers, thermistors, and an optical sensor were installed on a connection of interest. Figure 1 shows the location of the connection instrumented in a section of the rollercoaster and the location of the left-front strain rosette. The connection consists of a bracket and is located near the midspan between two columns and approximately 10 meters (32.8 ft) high. Two circular rails, running along the rollercoaster structure, guide the rollercoaster train. These rails are connected to a 38.1 mm (1.5 inch) thick steel plate bracket which connects to the main support girder located in the lower part of the rollercoaster's superstructure. The rail tubes, the brackets, and the support girder are welded and made of ASTM A572 grade 50 steel. Data collected from 10 rides under 4 different loading conditions is used for the estimation of fatigue life of the connection.

Figure 1 Instrumented bracket location. Close-up view of instrumentation.

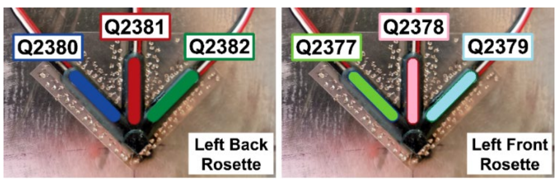

Figure 2. Left side strain rosettes installed on the roller coaster instrumented bracket

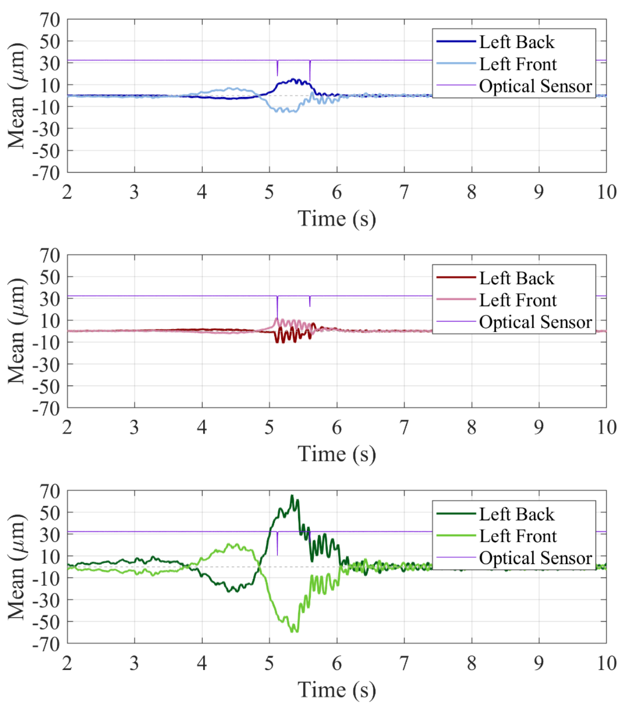

Figure 3. Strain data sample from the left-back and left-front rosette

Four strain rosettes are installed at 50.8 mm (2 inches) from the weld toe connecting the bracket to the main girder. Figure 2 shows a close view of two strain rosettes installed mirroring each other on the left side of the bracket. These are color coded to match the measured response graph lines colors. Mean values of strains recorded with a full train from the strain rosettes located in the left side of the bracket are shown in Figure 3. The optical sensor signal peaks downward when the rollercoaster train arrives and leaves the bracket. Tension and compression strain cycles are evident in all arms of the strain rosette when the train crosses the bracket. In addition, collected strains are mirroring each other in about the same magnitude experiencing tension in one side while compression in the other side of the bracket. Therefore, it is evident that the instrumented bracket is experiencing flexure stresses, mainly in the range of 4 to 6 seconds as shown in Figure 3.

Steel bridge case study

The Powder Mill Bridge (PMB), shown in Figure 4, is a three-span steel-girder bridge located in Barre, Massachusetts. The PMB is 47 m (154 ft) long and it carries two lanes of traffic over the Ware river. The PMB was instrumented during its construction in 2009. An instrumentation system comprised of strain gauges and other transducers was installed as a research prototype for the development of an SHM system. The onsite Data Acquisition (DAQ) system located underneath the bridge collects strain and temperature data 24/7 at 200 Hz. The bridge is a full-scale outdoor laboratory for SHM using short-term and long-term bridge response measurements.

Figure 4 Powder Mill Bridge (PMB) over the Ware River in Barre, MA

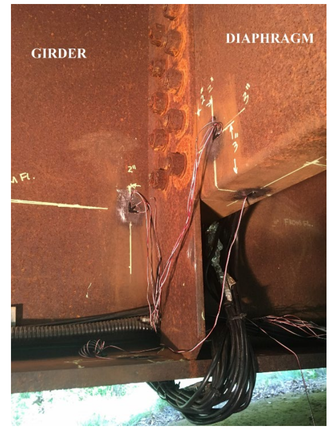

Figure 5 Instrumented connection

A connection was instrumented to determine the effect of multiaxial stresses and fatigue life. The connection instrumented connects a diaphragm near the south abutment to an interior girder (see Figure 5). Two strain rosettes and two single strain gauges were places. Strain rosettes are located on the web of the girder and the diaphragm while single strain gauges are located on the flanges.

FATIGUE ANALYSIS: UNIAXIAL VS MULTIAXIAL PROCEDURES

Rollercoaster case study

Yield criteria based on principal stresses or Von Mises stresses is typically used for fatigue life estimations when assuming a uniaxial behavior. However, when a component is subjected to multiaxial non-proportional loading, the orientation and magnitude of principal stresses vary with time leading to overestimates of remining fatigue life [7]. When multiaxial non-proportional stresses are evident, the critical plane method has shown to be effective at predicting remaining fatigue life [8]. The critical plane is defined as the plane orientation that causes the most fatigue damaging. This approach consists of examining the detailed stress states on several potential 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 multiaxial loadings [9]. In addition, it can be applied to different types of material besides steels such as elastomeric materials [10].

Figure 6 shows the variation of the principal stress orientation calculated using strains collected in the left-front side rosette for one full ride. In the range of 4 to 6 seconds, this graph demonstrates that the orientation of principal stresses does change. This variation was observed in all four rosettes. Outside that range, measured strains were close to ambient levels as shown in Figure 3; Thus, such changes in the orientation as shown in Figure 6 shall not be considered when determining if multiaxial effects should be assumed. This figure demonstrates that multiaxial non-proportional effects should be considered for this connection when estimating remaining fatigue life.

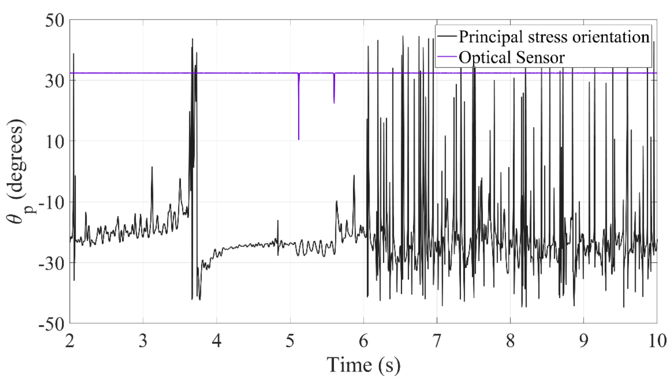

Figure 6 Rollercoaster's variation of principal stress orientation over time at left-front rosette

Furthermore, Figure 7 compares shear and normal strains the front-left side rosette. For proportional loading histories this comparison will result in a linear relationship [11]. However, the strains experienced by the rollercoaster shown to be randomly out of phase. 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 principal stresses.

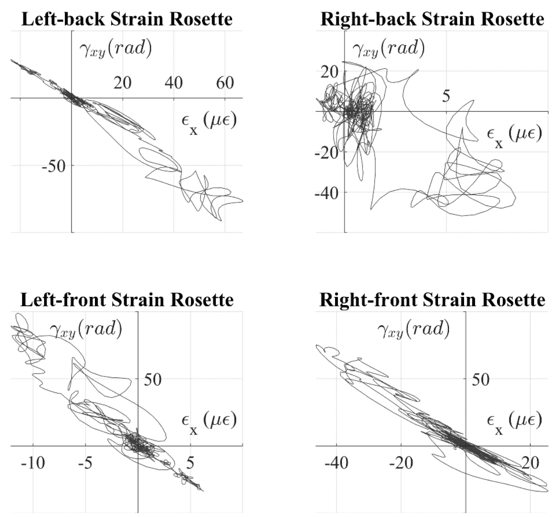

Figure 7 Rollercoaster's normal versus shear strains

Findley's parameter is used to determine the location of the critical plane. Findley proposed a linear combination of shear stress amplitude and the maximum normal stress experience during that cycle. The maximum value of the combination of cyclic shear stress amplitudes and maximum normal stress determines the location of the critical plane [3].

$$\left(\frac{\Delta\tau}{2} + k\sigma_{n,max}\right)_{MAX} = \tau_f^*\left(N_f\right)^b \qquad (1)$$

where,

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

The constant $\boldsymbol{k}$ is the material coefficient. This constant is found to be between 0.2 and 0.3 for ductile materials (Bruun and Härkegard, 2015). $\boldsymbol{\tau_f'}$ is torsional fatigue strength, $\boldsymbol{b}$ the fatigue exponent, and $\boldsymbol{N_f}$ the number of cycles to fatigue failure of the material. The right side of Eq. (1) corresponds to the elastic part of a torsion-based S-N curve. The number of stress cycles within the shear stress history at the critical plane is determined using a rain-flow counting algorithm. For comparison purpose, uniaxial fatigue life is calculated using a grade 50 steel axial based S-N curve [13] and the rain-flow counting algorithm using principal stresses. Failure is assumed to occur when the ratio of number of cycles of operation at a stress range to the total number of cycles reaches a value of one.

Table 1. Rollercoaster's summary of remaining fatigue life

	Strain rosette location (remaining fatigue life in years)			
Method	**Left-back**	**Right-back**	**Left-front**	**Right-front**
Critical plane	3.4E+13	2.7E+14	9.4E+14	3.8E+16
Principal stresses	8.3E+14	4.6E+15	7.6E+17	1.2E+18

Fatigue life estimates obtained show infinite fatigue life at all strain rosette locations using both the critical plane method and principal stresses. However, the years of remaining fatigue life estimated using the critical method are consistently less than the years calculated using uniaxial fatigue procedures. It should be noted that fatigue life predictions presented in Table 1 exclude the presence of the weld. This simplification was made for comparison of fatigue predictions using the critical plane and principal stress methods.

Steel bridge case study

Given the complexity of bridge structures, connections can experience multiaxial distribution of stresses. Evaluation of bridge fatigue life is usually performed using a single strain gage. Typically, when placing strain gages the orientation of tensile stresses is first well known for the member or the component tested. Therefore, strain gages are placed in this orientation [14]–[16]. However, in more complex details or connections such as the bridge diaphragm to girder connection shown in Figure 5 orientation of principal stresses might vary through a loading history. In this type of connections strain rosettes should be placed to have a better understanding of the distribution of stresses.

Data from the strain rosettes placed on the web of the girder and the web of the diaphragm are used to determine if multiaxial stresses are evident in this connection. Figure 8 shows the variation of principal stresses orientation over 40 seconds of data collected at the PMB. During this time about three traffic events are evident in strain histories. These plots show a high variation of principal stresses over time.

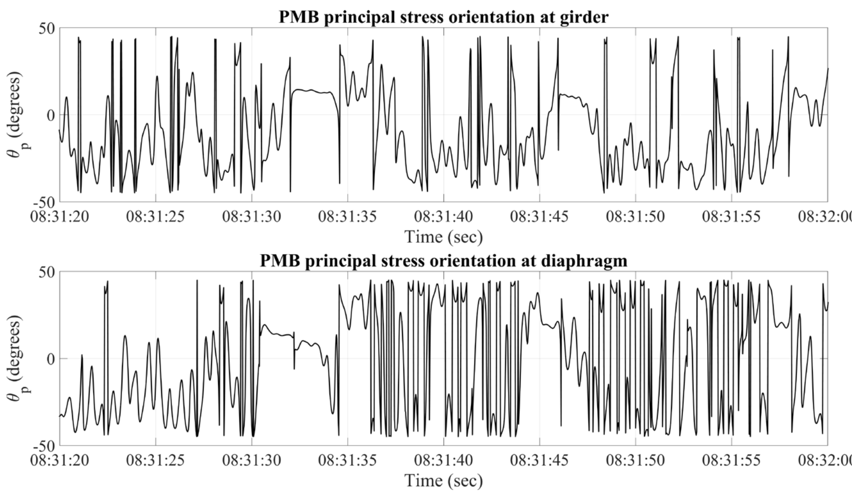

Figure 8 PMB's variation of principal stress orientation over time at main girder and diaphragm

A direct comparison between normal and shear strains can also be used to describe multiaxial stresses. If there is a linear relationship between these strains or stresses, multiaxial stresses act proportionally. On the contrary, if the interaction is close to a circle time history of normal and shear stresses are about 90 degrees out of phase. Figure 9 shows the interaction of shear and normal strains for the strain rosettes located on the girder and the diaphragm at the PMB. The plots show that there is a high phase difference between time histories of normal and shear strains at the girder. Although, the relationship between shear and normal strains at the diaphragm shows to be closer to a line, representing proportional multiaxial stresses, principal stresses orientations show some variation.

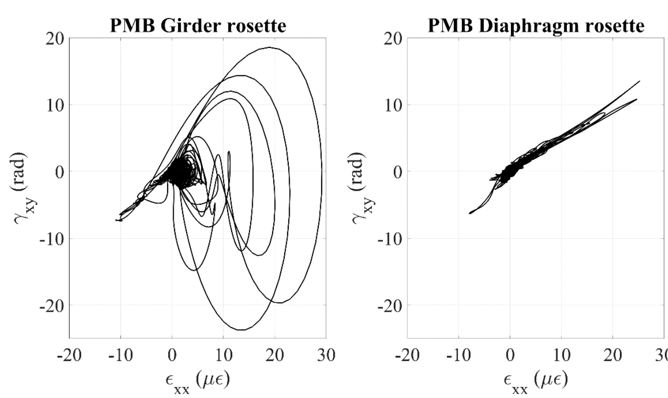

Figure 9 PMB's normal versus shear strains at rosettes located on the girder and diaphragm

Remaining fatigue life is estimated using principal stresses and Findley's parameter to determine the effect of multiaxial stresses at the location of the strain rosettes. Generalized axial and torsional S-N curves for grade 50 steel tested by Kurath and Fatemi (1990) are used to estimate remaining fatigue life. Table 2 summarizes remaining fatigue life estimates. These estimates are based solely on the data collected from strain rosettes.

Table 2. PMB's summary of remaining fatigue life at strain rosettes

	Strain rosette location (remaining fatigue life in years)	
Method	**Girder**	**Diaphragm**
Critical plane	8.8E+14	2.7E+15
Principal stresses	1.5E+20	6.2E+19

Remaining fatigue life is estimated to be infinite. However, when looking at the finite number of remaining fatigue life lower values are obtained if multiaxial effects are taken into consideration. These preliminary estimates show that there is a significant difference when non-proportional stresses are evident. Such is the case with estimates base on data collected in the girder's web. Fatigue life estimates are lower when using the critical plane method compared to estimates based on the rosette located at the diaphragm. However, when using principal stresses fatigue life seems to be overestimated.

CONCLUSIONS AND FUTURE WORK

Remaining fatigue life is estimated based on data collected from two different connections. A rollercoaster connection was instrumented and tested under different loading configurations while a steel bridge connection was instrumented and tested under daily traffic. Multiaxiality was determined by comparing shear and normal strains and the orientation of principal stresses. Uniaxial and multiaxial fatigue life assumptions were used to examine the effect of multiaxial stresses acting in the instrumented connections. Uniaxial and multiaxial fatigue analysis methods are compared. The critical plane method is used for the estimation of multiaxial fatigue life and compared to results obtained assuming a uniaxial behavior. As expected, both methodologies resulted in infinite life estimates. However, when the critical plane method is used the total number of estimated remaining fatigue years is lower than estimated remaining fatigue assuming that the orientation of principal stresses is constant. Therefore, it is concluded that:

1. Commonly used uniaxial fatigue analysis methods are insufficient in complex structures that experience variable amplitude, multiaxial, and non-proportional loading.
2. Although, simplifications were made to make a fair and direct comparison possible between fatigue analysis methods, preliminary results demonstrate that assuming uniaxial behavior can lead to overestimates of remaining fatigue life. Fatigue estimates using the critical plane method resulted in lower fatigue life estimate compared to uniaxial estimate for the connections studied.
3. 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. Given the lack of torsional S-N curves available for different types of connections, further work is needed to determine the effect of multiaxial stresses on different connection geometries and types.
4. The presence of welds and bolts cause stress concentrations that significantly decrease in fatigue life and should be considered in final estimates of remaining fatigue life. Although several design codes and standard account for different types of geometries, the curves provided are insufficient in complex structures that experience variable amplitude, multiaxial, and non-proportional loading.
5. The methodology proposed is anticipated to be used for realistic fatigue prognosis of any complex connection. Having a realistic approach will help in assessing critical needs related to maintenance procedures of complex structures, visual inspection techniques, and evaluation tools for infrastructure networks.

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