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Review on Fatigue Analysis Using Field Measurement Data

Ganesh.L.G¹, Srinidhi Bhat.K¹, Pradeepa.S², Anita.j³

UG Students, Department of Civil Engineering, Sir.M.Visvesvaraya Institute of Technology, Bangalore, India¹

Assistant Professor, Department of Civil Engineering, Sir.M.Visvesvaraya Institute of Technology, Bangalore, India²

Assistant Professor, Department of Civil Engineering, Sir.M.Visvesvaraya Institute of Technology, Bangalore, India³

ABSTRACT: Fatigue is the weakening of materials caused by repeatedly applied loads. It is the progressive & localized structural damage that occurs when the material is subjected to cyclic loading. Fatigue analysis using field measurement is of utmost importance as theoretical methods of analysis of fatigue are not accurate. Fatigue failure is defined as the tendency of material to fracture by means of progressive brittle cracking under repeated alternating (or) cyclic stresses of an intensity considerably below the normal strength. Fatigue failure is an immediate (or) sudden phenomenon, hence to avoid the disaster which may follow fatigue analysis is essential.

This paper presents review on fatigue analysis using field measured data. When analyzing data obtained from field measurements, methods are needed to properly evaluate fatigue damage. The traditional method of converting distribution of stress cycles used for a rainflow analysis to an effective stress range using Palmgren-Miner's rule has some shortcomings. Namely, the calculation of the effective stress range can be skewed if there is a large percentage of cycles in the first few bins. A new method, denoted as the index stress range has been developed. This method has advantages over effective stress range since this method is targeted for evaluating & comparing fatigue damage at multiple locations in a structural system based on rainflow data from strain gages. This analysis has huge range of applications in estimating the remaining fatigue life of the steel bridges & also it is required especially for decisions on structure replacement, deck replacement, (or) other major retrofits in steel bridges.

KEYWORDS: Fatigue, rainflow analysis, effective stress range, index stress range.

I.INTRODUCTION

Fatigue is the weakening of materials caused by repeatedly applied loads. It is the progressive & localized structural damage that occurs when the material is subjected to cyclic loading (or) Fatigue is the process of crack growth in steel structures due to cyclic variations in the applied stress. In high cycles fatigue, the magnitudes of the stress are often well below the yield stress of the material; however, stress concentrations due to the presence of defects or microcracks in the material and/or residual stresses lead to crack growth. In these situations, the number of cycles necessary for the crack to grow to the critical size, such that brittle fracture occurs, range from several hundred thousand to several million.

The initial cracks in the material often initiate from small flaws resulting from the manufacturing and/or fabrication processes. In rolled shapes, the flaws arise from surface and edge imperfections, irregularities in mill scale, inclusions, and from the mechanical notches due to handling, straightening, cutting, and shearing. When bolts or rivets are used, additional flaws can be introduced from drilling or punching the holes. Flaws are generated from the welding process when the weld has partial penetration, lack of fusion, micro flaws at the weld toe, and start and stop locations. While flaws in the welds cannot be totally eliminated, proper welding procedures and inspections can help minimize the frequency and size of the flaws.

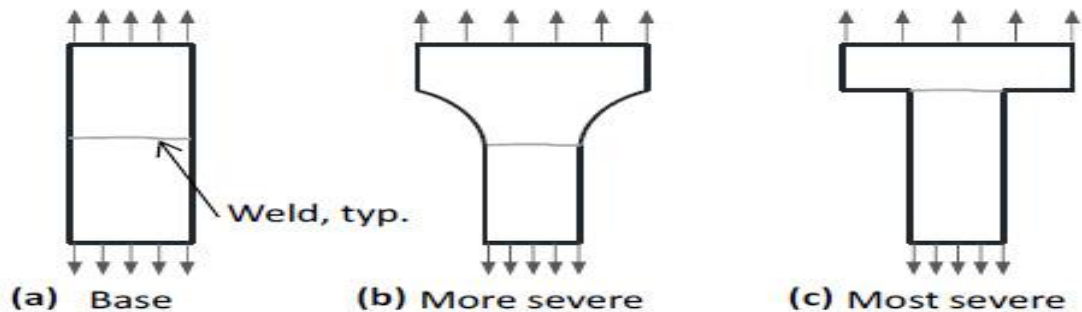
The geometric shape of a member or detail also affects the fatigue behavior. Changes in the geometry often result in stress concentrations that reduce the fatigue resistance of a specimen. The magnitude of the stress concentration is related to the severity of the change in geometry. For instance, three shapes are shown in Figure shown below

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The specimen with no change in geometry (Figure (a)) will have the best fatigue behavior. The specimen on the right (Figure (c)) will have the most severe stress concentration due to the highly localized change in geometry. Compared with the other two details, the middle detail (Figure (b)) will have an intermediate stress concentration. The change in geometry in Case B will produce a stress concentration that will lead to lower fatigue resistance compared with case A; however, the fatigue behavior for Case B would be better than Case C because the change in geometry is more gradual.

In welded structures, such as steel bridges, the primary variables used to evaluate the fatigue performance are the magnitude of the stress range & the type of detail. The minimum, mean & maximum stress don't significantly affect fatigue behavior in welded structures due to high residual stresses. Those parameters can be very important in the certain fatigue applications (i.e, airplanes); however, they are not a major concern in the welded steel bridges. In steel bridges design, the typical arrays of details are classified into various design categories, each having a different fatigue performance. If a new detail is desired, the failure resistance can be determined both experimentally & numerically. And also the initial crack size & fracture toughness also affect the fatigue behavior.

Theoretical methods such as;

1. Fatigue analysis using stress-life method.
2. Fatigue analysis using fracture mechanics approach.
3. Fatigue analysis using strain-life method. etc

Cannot evaluate the remaining life of the steel structures such as bridges accurately.

The majority of engineering failures are caused by fatigue. Fatigue failure is defined as the tendency of a material to fracture by means of progressive brittle cracking under repeated alternating (or) cycle stresses of a intensity considerable below the normal strength. Although the fracture is of a brittle type, it may take some time to propagate, depending on both the intensity & frequency of the stress cycles. Nevertheless, there is very little, if any warning before failure if crack is not noticed. The number of cycles required to cause fatigue failure at a particular peak stress is generally quite large, but it decreases as the stress is increased. For some mild steels, cylindrical stresses can be continued indefinitely provided the peak stress (sometimes called fatigue strength) is below the endurance limit value.

A good example of fatigue failure is breaking a thin steel rod (or) wire with your hands after bending it back and forth several times in the same place.

Fundamental requirements during design, manufacturing & construction for avoiding fatigue failure are different for different cases & should be considered during the design phase.

As mentioned above, fatigue failure is an immediate or sudden phenomenon, hence to avoid the disaster which may lead to loss fatigue analysis is very much essential.

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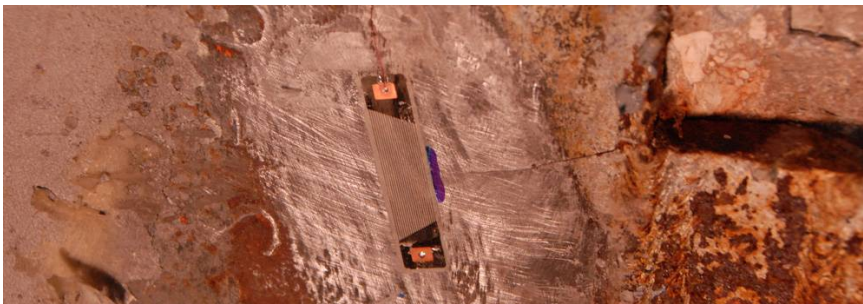
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2. Field data measurement

The field data required for the fatigue analysis will be obtained from the strain gages & crack propagation gages. The installation of the strain gages and the crack propagation gages are shown in figure given below.



Strain gage located on the top flange of the longitudinal girder of Bridge approximately 2 ft away from the connection of the floor beam.



Crack propagation gage installed at tip of active crack at floor beam 34 of Bridge

Two types of data acquisition systems from National Instruments (NI) were used to obtain dynamic strain data at the four bridge sites. The wired (CompactRIO) and wireless (WSN) systems were used to determine the fatigue cycles from vehicles crossing the bridge using the simplified rainflow algorithm, and the resulting distribution of stress ranges were used to calculate the remaining fatigue life. Strain gages were the primary type of sensor used at the bridge sites. Strains were converted to stresses using Hooke's Law and a modulus of elasticity for steel of 29,000 ksi.

The NI CompactRIO is a wired system that is capable of high-resolution, configurable data acquisition and control. For the bridge sites, NI-9237 modules were combined with the CompactRIO to acquire high-speed quarter-, half-, and full-bridge measurements. Each module supports four channels and each channel has a separate, 24-bit analog-to-digital converter (ADC). The module utilizes field-programmable gate arrays (FPGA) to produce hardware-timed measurements that can be synchronized across modules. Using the internal master timebase, the module supports sampling rates between 1,613 Hz and 50,000 Hz. A 2.5-V excitation was used along with 350- Ω quarter-bridge completion resistors.

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CompactRIO data acquisition system with NI-9237 modules (wired).

The other data acquisition system employed at the bridge sites is the Wireless Sensor Network (WSN) platform from NI. With such a wireless system, sensors are connected to nodes that acquire data and send the data wirelessly to a gateway/computer where it can be stored temporarily or permanently. The gateway creates the wireless network that enables the nodes to transmit data. The WSN platform utilizes a narrow-band protocol (IEEE 802.15.4) to transmit data. The wireless strain node, WSN-3214, is capable of capturing dynamic data from four analog channels. A variety of sensors can be used, including quarter-bridge (built-in 350- Ω and 1,000- Ω completion resistors), half-bridge, and full-



Wireless strain node data acquisition system (WSN-3214).

bridge inputs with a 2.0-V bridge excitation. The embedded, Texas Instrument MSP430 microprocessor has the ability to run LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) WSN graphical programs, thereby enabling onboard data processing at the node. Using LabVIEW WSN, the strain node can be easily customized for a particular application. The sensors (primarily strain gages or crack propagation gages) need to be properly chosen and installed to survive at least ten years. The harsh environmental conditions, severe temperature ranges and humidity fluctuations, make monitoring bridges challenging. A wide variety of strain sensors have been tested in different environmental conditions to identify robust gages and installation techniques.

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3. Techniques for fatigue analysis

When analyzing data obtained from field measurements, methods are needed to properly evaluate fatigue damage. The traditional method of converting the distribution of stress cycles used for a rainflow analysis to an effective stress range using Palmgren-Miner's rule has some shortcomings. Namely, the calculation of the effective stress range can be skewed if there is a large percentage of the cycles in the first few bins. As such, even if two different stress spectra generate the same amount of fatigue damage, the spectra will likely produce different values for the effective stress range.

A new method, denoted as the index stress range, was developed as part of this research investigation. The method is targeted for evaluating and comparing fatigue damage at multiple locations in a structural system based on rainflow data from strain gages. The index stress range is advantageous to the effective stress range because the extent of fatigue damage induced at the location of each strain gage is normalized. Rather than calculating the effective stress range for a given number of cycles, the number of equivalent cycles at an index stress range is determined for a set amount of induced fatigue damage.

Simplified rainflow analysis

The first step to evaluate the fatigue damage using data from field measurements in a bridge is to determine the distribution of stress cycles. The simplified rainflow method was implemented in LabVIEW for use in the research outlined in this dissertation. LabVIEW is a graphical programming language that was developed by National Instruments (NI). It can be used with many different computer platforms; however, LabVIEW is ideally compatible with NI hardware. The program can be executed offline on a Windows-based computer or in realtime on NI hardware. The user inputs the data (strain/stress history), the size of the bins for the histogram, the number of total bins, the minimum amplitude to count, and the length of the analysis. The program will reduce the strain/stress history into peaks and valleys, save the peaks and valleys into memory, and determine the amplitude of each cycle and put it into the appropriate bin of the rainflow histogram. The duration of the analysis is an important consideration. If the duration is too long, a potentially large, fictitious cycle due to the drift of the strain gage with temperature may be counted. If the duration is too short, then the count could be biased due to partial cycles being counted as full cycles. A length of 30 minutes was chosen for all of the analyses in this dissertation. In 30 minutes, the drift of the gage due to temperature is generally minimal and the time is long enough to provide a realistic count.

Amount of fatigue damage

The primary goal of any monitoring project is to determine the amount of fatigue damage that is induced during the monitoring period. The damage is then typically used to estimate the remaining fatigue life by projecting damage in years prior to the monitoring period and in the future. AASHTO LRFD Specifications (2010) relates the number of cycles to failure for a given stress range using Equation mentioned below the equation is often plotted and referred to as S-N curves. Thus, the fatigue damage is described by the number of cycles times the stress range cubed, and the fatigue resistance is A.

$$N_f = \frac{A}{(S_r)^3}$$

N_f = design number of cycles until failure at S_r

A = fatigue constant for detail category, defined by AASHTO LRFD Specifications (2010)

S_r = constant-amplitude stress range

Because bridges experience variable-amplitude stress ranges, it is useful to transform the distribution of stress ranges into a single, constant-amplitude stress range that induces an equivalent amount of damage. In addition, because the S-N curves are expressed in terms of the number of constant-amplitude cycles, determining the equivalent stress range is useful for both design and analysis. The most common way to relate the variable-amplitude stress ranges to a single stress range is to calculate the effective stress range using Palmgren-Miner's rule. It is difficult to compare the amount of fatigue damage for different gage locations using the effective stress range because the number of measured cycles must be considered along with the effective stress range. As part of this research study, a new method for assessing and comparing fatigue damage among different locations along a given bridge or within an inventory of bridges was developed. Palmgren-Miner's rule is also utilized with the index stress range. However, because the index

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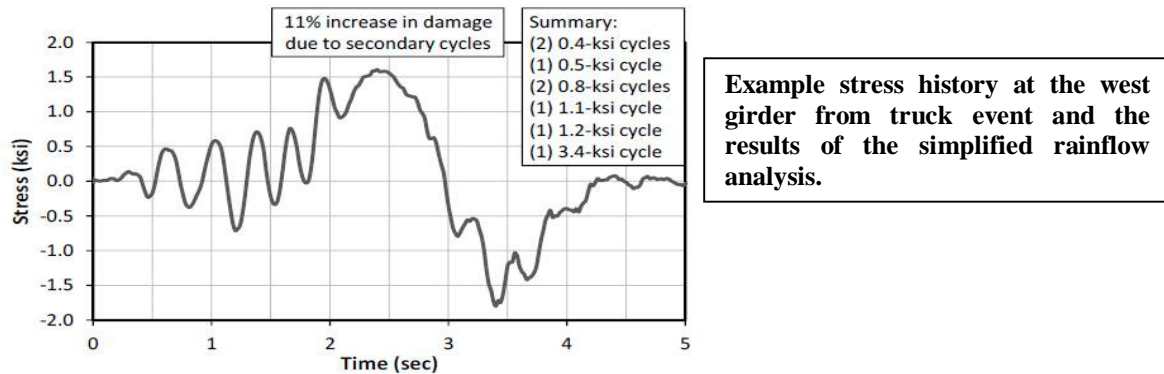
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stress range is the same for each instrumented location, the metric of damage becomes only the equivalent number of cycles at the index stress range. Therefore, the response at different locations can be compared directly using only the equivalent number of cycles. Palmgren-Miner's rule is the most popular cumulative damage theory utilized in the USA for dealing with fatigue-related damage because the simple method has been shown to agree well with test results (ASCE 1982). It is used by AASHTO to relate variable-amplitude loading to the fatigue results of constant-amplitude loading. Nonlinear, cumulative damage theories have been proposed by some researchers. However, the equations are more complicated to use and the results are not consistently better than a linear damage theory.

There are two shortcomings of Palmgren-Miner's rule. First, the method does not consider the sequence of loading. In some cases, the sequence has been shown to impact the fatigue behavior. For instance, if an overload stress range occurs with low frequency after many low stress ranges, it has been found to increase the fatigue strength of the specimen (ASCE 1982). Yet, Palmgren-Miner's rule does not account for such interaction. Palmgren-Miner's rule also does not account for any influence that the average stress may have on the fatigue life of the specimen. However, for welded structures with high residual stresses, the average stress does not have a large influence on the fatigue life. For structures subject to random loading and relatively few overloaded stress ranges, Palmgren-Miner's rule can adequately describe the damage.

A concern of applying Palmgren-Miner's rule is how to deal with cycles with an amplitude less than the constant-amplitude fatigue limit (CAFL). Assuming that all cycles contribute to the damage is equivalent to assuming that the value for the fatigue threshold stress intensity factor is zero. Some researchers have proposed truncating all cycles less than 25-50% of the CAFL, whereas European practice weights the lower stress ranges differently. The European practice has been shown to be unconservative for some welded longitudinal attachments. In addition, Swenson & Frank (1984) have shown that all cycles can contribute to the accumulation of fatigue damage, even cycles with amplitudes less than the CAFL. A histogram of stress ranges for fourteen days of data for the east girder at Bridge



is presented in Figure. The first seven days occurred in April 2011 and the second seven days in July 2011. The strain gages were attached to a connection that is classified as AASHTO Category E. The stress history was evaluated in 30-minute periods and

cycles less than 0.06 ksi were considered to be caused by electromechanical noise within the data acquisition system and truncated. The rainflow bins were 0.15-ksi wide. A total of 800,000 cycles were measured during the two weeks (daily average is 57,100 cycles), with a maximum stress range of 20.8 ksi. The histogram was used to compare the two methods for evaluating the amount of fatigue damage: (1) the effective stress range and (2) the index stress range. The following two subsections document the results from the two methods.

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Fatigue constant (A) and constant-amplitude fatigue limit (CAFL) for each fatigue detail category (AASHTO LRFD Specifications 2010)

Category	Fatigue constant, A (ksi ³)	CAFL (ksi)
A	250×10 ⁸	24.0
B	120×10 ⁸	16.0
B'	61×10 ⁸	12.0
C	44×10 ⁸	10.0
C'	44×10 ⁸	12.0
D	22×10 ⁸	7.0
E	11×10 ⁸	4.5
E'	3.9×10 ⁸	2.6

Effective stress range

The effective stress range is an efficient method to relate the cycles from a spectrum of stress ranges to a single, equivalent stress range. Rather than listing each stress range that was determined from a rainflow analysis, the ranges are typically sorted into bins. All of the cycles in a particular bin are assumed to have the same stress range as the average stress of the bin. As such, the damage accumulation index and effective stress range for a rainflow histogram can be calculated using Equation 3-2 and Equation 3-3, respectively.

$$D = \sum \frac{n_j}{N_{f,j}} = \frac{\sum n_j \times \bar{S}_j^3}{A} \quad \text{Equation 3-2}$$

where

- n_j = measured number of cycles in bin corresponding to \bar{S}_j recorded during monitoring period
- $N_{f,j}$ = design number of cycles until failure at \bar{S}_j
- \bar{S}_j = average stress range for bin j (ksi)
- A = fatigue constant for detail category, defined by AASHTO LRFD Design Specifications (2010) (ksi³)

$$S_{re} = \left(\frac{\sum n_j \times \bar{S}_j^3}{N_m} \right)^{1/3} \quad \text{Equation 3-3}$$

where

- S_{re} = effective stress range for N_m cycles (ksi)
- N_m = total number of stress cycles measured during monitoring period

If the damage accumulation index is graphed on a log-log S-N plot, different levels of D plot parallel to the descending branch of the design S-N curve for the given fatigue category (Figure 3-3). The lines plot parallel because the damage accumulation index can also be defined as the ratio of the number of cycles experienced to the design

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fatigue life. As demonstrated in the figure, the damage accumulation index is larger as it gets closer to the design S-N curve for the fatigue category.

In principle, the effective stress range is calculated for a given number of measured cycles and damage accumulation index. This is shown graphically in Figure 3-4. If the number of cycles change, but the damage stays constant, the effective stress range can change. As such, calculating the effective stress range does not provide a relative measure of damage at a gage location because each set of data could produce a different set of effective stress ranges. With effective stress ranges that vary depending on the monitoring period and number of cycles captured in the first few bins of a rainflow histogram, comparing multiple gage locations is very difficult. The effective stress range for the example histogram that was presented for Bridge in Figure 3-2 was calculated to be 2.24 ksi for the 800,000 cycles recorded during the 14-day period. The effects of truncating low-amplitude stress cycles and variation in traffic volume based on the day of the week on the calculated effective stress range. A new method, index stress range, was developed to overcome the limitations of using the effective stress range, and allow relative comparison between gage locations.

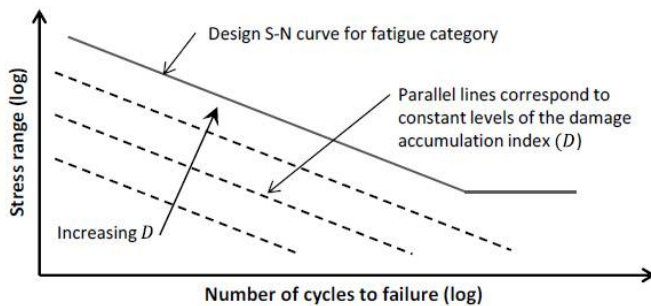


Figure 3-3: Different levels of the damage accumulation index on a S-N graph.

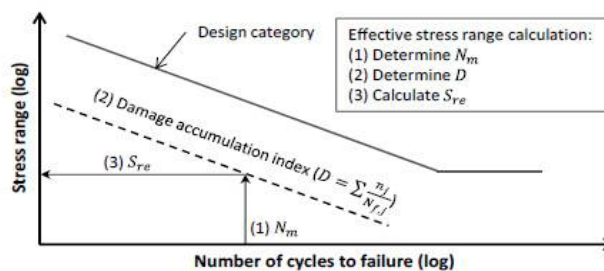


Figure 3-4: Graphical representation of the method for determining the effective stress range.

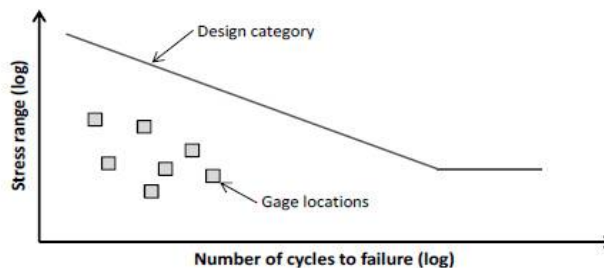


Figure 3-5: Varying sets of effective stress ranges and measured cycles for different gage locations.

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Index stress range

Relative damage accumulation is a useful tool for bridge owners because it can identify problems within a single bridge or across a bridge inventory. If the locations of highest damage accumulation are known, inspection efforts can be focused on such locations. Fatigue damage is characterized by the number of cycles at a specific stress range; thus, either the number of the cycles or the stress range has to be the same to compare two locations directly.

An index stress range was developed as a method to evaluate the relative extent of fatigue accumulation for different locations along the same bridge. It can also be used to compare damage among different bridges. With the index stress range, all measured data, whether in the form of an effective stress range or a distribution of stress ranges, are normalized to the same stress range, which is selected by the engineer. By normalizing the data to an index stress range, the number of cycles at the selected stress range becomes the direct metric of relative fatigue damage: twice as many cycles at the same index stress range causes twice the fatigue damage.

The index stress range can be derived using two approaches: (1) with an effective stress range or (2) with a histogram of stress ranges. If the effective stress range obtained from measured data has already been calculated, it can be indexed to an arbitrary stress range as long as the damage accumulation index (D) stays the same. The damage index can be defined for an effective stress range using Equation given below

$$D = \frac{N_m \times S_{re}^3}{A}$$

Because damage is characterized by the number of cycles at a specific stress range and the AASHTO detail category constant does not change with the stress range, the number of cycles at the index stress range is modified equation mentioned below to keep the damage index the same as at the effective stress range. By keeping the damage index the same, the remaining fatigue life will be the same whether the index stress range (with cycles at index stress range) or the effective stress range (with cycles at effective stress range) is used for the calculation.

$$N_i(S_{ri}) = N_m \times \frac{S_{re}^3}{S_{ri}^3}$$

where

$$N_i(S_{ri}) = \text{number of equivalent cycles at } S_{ri}$$

$$S_{ri} = \text{index stress range}$$

Because the number of cycles and corresponding stress range are needed to calculate the amount of fatigue damage, the index stress range can be referenced using the notation of Equation. By referencing the stress range, the damage accumulation index can be calculated easily or used to calculate the fatigue life. For instance, if an index level of 4.5 ksi is chosen, the notation for the number of cycles can be expressed as $N_i(4.5 \text{ ksi})$. A line over the top and a subscript (can be used to represent the daily average: $N_{d,i}(4.5 \text{ ksi})$). Other subscripts can be used for monthly (m) or yearly (y) averages.

By using an index stress range, the number of cycles is determined for an arbitrary stress range and damage index. In contrast, the effective stress range is determined from the number of measured cycles and damage index. The index

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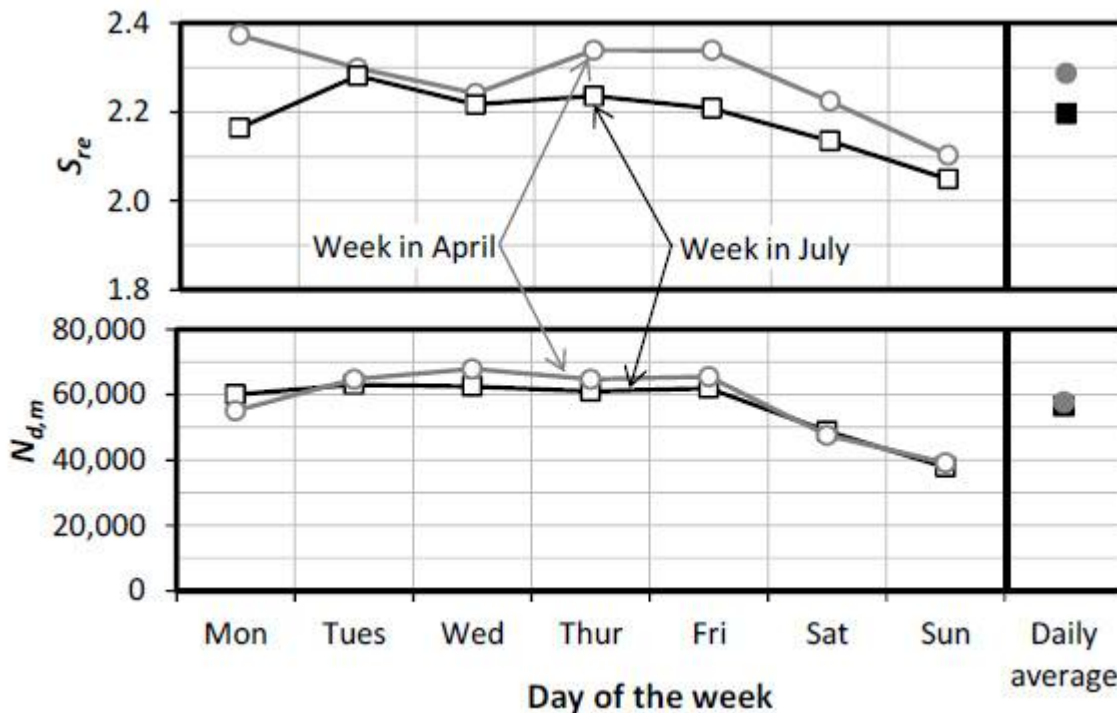
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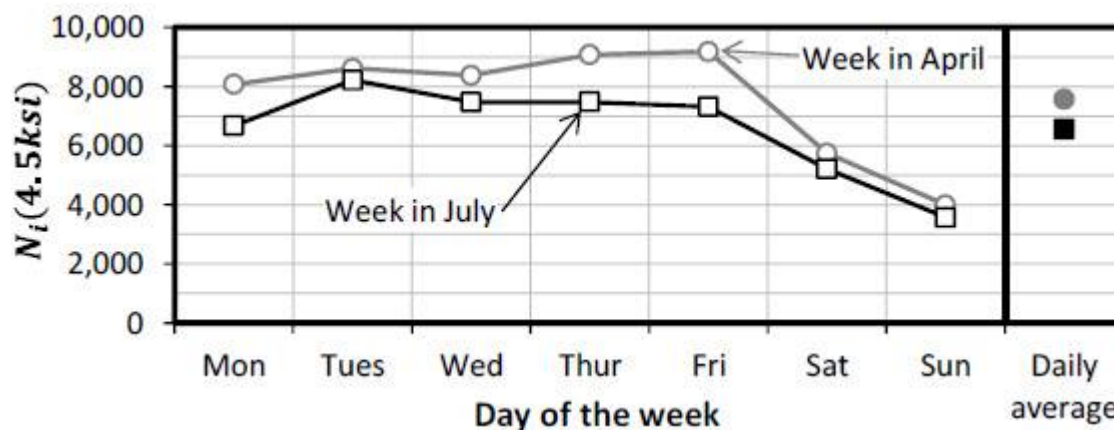
stress range can be set to any desired magnitude; however, a convenient value is the threshold stress of the given AASHTO detail category.

Comparison of Effective stress range & Index stress range

The relative merits of each method, effective stress range and index stress range, can be compared by evaluating the effects of truncation and daily traffic variations on the calculation of damage. If the lower stress ranges do not impact the accumulation of damage, the effect of truncating those lower rainflow bins should also be minimal. As much as 25-50% of the threshold stress range is recommended to be truncated.



Change in effective stress range and number of cycles with day of the week for Bridge



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Change in number of cycles at index stress range with day of the week for Bridge

In summary, the index stress range is a better indicator of damage because the damage is normalized. The method allows for easy comparison between different gage locations, days, and/or bridges because each set of data can be indexed to the same arbitrary stress range. Therefore, the number of cycles at the index stress range is the only value needed to compare two gage locations. Additionally, using the index stress range makes it easier to evaluate the variation in fatigue damage and characterize the benefit of a retrofit by tracking the daily changes in the fatigue damage. In constant, comparing two gage locations using the effective stress range is convoluted because the damage accumulation index has to be calculated. As such, the effective stress range and measured number of cycles have to be multiplied following Palmgren-Miner's rule for comparison of two gage locations. This fatigue analysis using field measurement data has huge range of applications in estimating the remaining fatigue life of the steel bridges & also it is required especially for decisions on structure replacement, deck replacement, (or) other major retrofits in steel bridges.

Characterization of fatigue damage

This section focuses on characterizing the fatigue damage by identifying which stress ranges are contributing the most to the damage. Because fatigue damage is proportional to the stress range cubed, the larger stress cycles are alarming. Though each cycle can cause a lot of damage, the larger cycles do not occur very often. As such, they may not significantly affect the accumulation of fatigue damage. The contribution of a stress range to damage and cumulative damage with stress range can be used to characterize the fatigue damage.

Contribution to damage

The contribution of a particular bin or stress range to the fatigue damage (d_j) across a histogram of stress ranges can be evaluated using Equation 3-8. The total fatigue damage for a monitoring period is the sum of all stress ranges. The damage accumulation index (D) can be calculated if the total fatigue damage is divided by the fatigue constant (A) for the particular detail.

$$d_j = n_j \times \bar{S}_j^3$$

where

$$d_j = \text{fatigue damage from bin } j$$

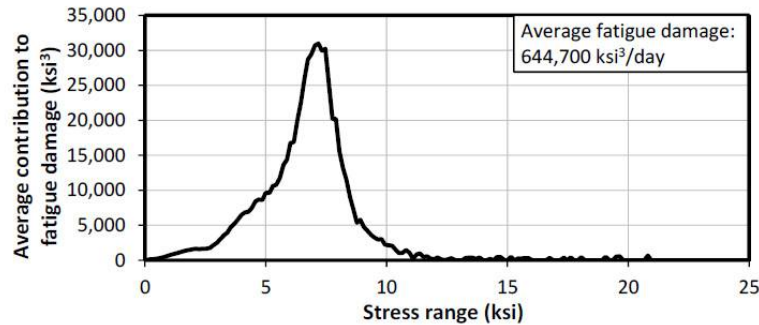
If Equation 3-8 is applied to the example histogram for Bridge A (Figure 3-2), the contribution of each bin can be calculated (Figure 3-14). The average fatigue damage for the data is 644,700 ksi³/day. The largest amount of damage occurred between stress ranges of 2 ksi and 10 ksi. The limits (2 ksi and 10 ksi) were determined based on the technique described in the next section. Despite the large number of cycles in the first few bins, the lower stress ranges did not significantly contribute to the accumulation of fatigue. This matches the result of truncating the lower stress ranges in Figure 3-8. The larger cycles also did not contribute significantly to the fatigue damage as seen by the small peaks in Figure 3-14. The contribution of stress cycles greater than 15 ksi is insignificant because there are so few occurrences of the larger stress ranges relative to the mid-level stress ranges.

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3-14 Contribution of each bin to the total fatigue damage during the 14-day monitoring period for Bridge

Cumulative damage

The contribution to damage can be formalized by calculating how much damage is accumulated by the measured stress ranges. Equation 3-10 can be used to calculate the cumulative stress range for a given bin. The method of index stress range could also be used to determine the cumulative damage, and it would produce an equation similar to Equation 3-10.

$$d_{cumulative,j} = \frac{\sum_0^j n_j \times \bar{S}_j^3}{d_{total}} \quad \text{Equation 3-10}$$

where

$d_{cumulative,j}$ = cumulative fatigue damage from bins 0 to j

d_{total} = sum of fatigue damage from all bins

The cumulative damage was calculated for the example histogram for Bridge. The cumulative damage graph was split into regions of lower 2.5% damage, middle 95% damage, and upper 2.5% damage (Figure 3-16). The graph shows that the majority of the damage was induced by stress cycles between 2 ksi and 10 ksi. The cumulative damage plot formalizes the conclusions from the contribution to damage plot: neither the lower or larger stress ranges contributed significantly to the accumulation of fatigue damage at this bridge. Many researchers truncate lower bins because the large number of cycles in the lower bins might affect the calculation of the effective stress range and the cycles are typically a result of electromechanical noise, rather than real fatigue cycles. For this bridge, the lower bins can be truncated with very little impact on the analysis because cycles below 1 ksi contributed less than 2.5% to the total damage. The damage at the site is dominated by typical truck traffic, whereas cycles greater than 10 ksi only contributed approximately 2.5% of the damage.

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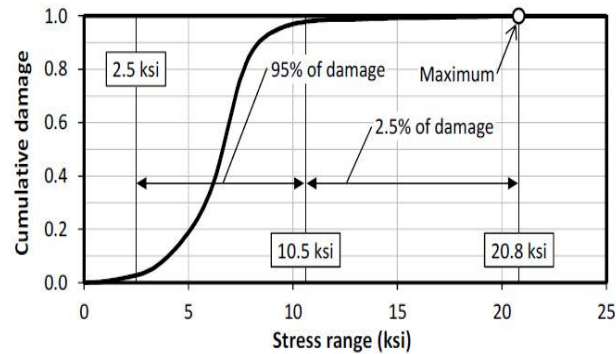


Figure 3-16: Average cumulative damage during the 14-day monitoring period for Bridge

IV. SUMMARY

Using the procedures described in this chapter, the amount of fatigue damage can be determined and characterized. The index stress range provides a method for assessing the relative damage accumulation between gage locations and/or bridges. Because the damage is normalized using the method, the number of cycles at the index stress range is a better indicator of damage. The method can also be used to calculate the contribution of damage from each stress range. Because both lower (electromechanical noise) and higher (possibility of a spike in the data acquisition system) stress ranges are questioned during a monitoring program, the impact of all stress ranges can be evaluated. If the cycles contribute more to the damage than expected those cycles can be analyzed further. Engineers can use judgment on how to handle low amplitude cycles in the absence of international agreement. However, in most cases, the lower cycles (less than 1.0 ksi) do not significantly contribute to fatigue damage and will be normalized by the index stress range.

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