Deterioration and Damage Analysis of Steel Bridge Decks

Fracture Mechanics Approach

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Abstract

Modeling Bridge Fatigue Life: Fracture Mechanics Approach. Sallem Ahmed (Graz University of Technology, Institute of Steel Structures) Harald Unterweger

A study on fracture mechanics was conducted for a representative detail of a steel bridge deck using a Matlab simulation to obtain a better understanding of bridge damage and deterioration details with fatigue failure. The service life of a bridge is typically controlled by fatigue failure. Fatigue failure is due to the repetitive loads and stress cycles that causes the weakening of a bridge. One symptom of fatigue on a bridge is cracking. Fatigue models typically show a relationship between the magnitude of stress cycles due to loads and the repetition of the load. However, what they neglect to display is the direct relation of high concentrated loads causing initial cracks and how the continuous repetition of loads continues to expand the crack to reach a length where corrective maintenance is required. The focus of this paper is to discuss the damage and deterioration of a steel bridge deck detail by the fracture mechanics approach and find a correlation that helps to better model bridge remaining service life. Moreover, this study compares the damage of two load models. The first load model is a database of class 5 trucks on a steel deck and the second load model is using a database of class 9 trucks. The class 5 trucks have two axles and class 9 trucks have 5 axles. The results of this study show that the steel deck is able to last approximately 51 more years under the class 9 truck load case than the class 5 truck load case. This means that the fatigue life span favors a model with lower axle loads with more repetition of the axle loads than higher axle loads with less repetition. Furthermore, the class 9 truck load case was able to carry 8.79 million kips extra than the class 5 truck case. This means that by lowering the maximum stress cycle, we can significantly increase the fatigue life of a bridge deck plate and also increase the amount of goods transported over the lifetime of the bridge deck. Lastly, total fatigue life of the bridge deck plate under class 9 scenario is 125.99 years, while the total life span of the bridge deck plate under class 5 scenario is 74.69 years. Also, the total amount of cargo transported by the class 9 truck scenario is approximately 21.78 million kips and the total amount of cargo transported by the class 5 truck scenario is approximately 12.99 million kips.

Introduction

Maintenance of a bridge is typically scheduled based on the condition of the bridge. After a certain condition of the bridge is considered not suitable enough for driver's safety and comfort on the road, the damaged parts will be maintained. The condition is typically evaluated on a rating scale. Depending on the location of where the bridge, the rating may vary on the regions rules and regulation of bridge condition standards.

The United States follows the National Bridge Inspection (NBI) Rating for the condition criteria for bridges. The NBI system gives several items to evaluate a bridge and the conditions criteria of a bridges structure which are evaluated in item numbers 58 to 60 and 62 and the criteria may vary depending on the bridge's deck material. Item 58 evaluates bridge deck condition ratings. Item 59 evaluates the superstructure condition rating. Item 60 evaluates the substructure condition rating and Item 62 evaluates the Culvert condition rating. The NBI rating for the bridge condition is on a scale of 0-9 with code N and 99 as place holders for the position as a code for non-valuable entered data. Table 1 describes the NBI condition rating criteria for the deck, superstructure and substructure of the bridge.

Table 1: Items 58, 59, 60 - Condition Ratings: Deck, Superstructure, Substructure [6]

Code	Criteria
N	NOT APPLICABLE
9	EXCELLENT CONDITION
8	VERY GOOD CONDITION - no problems noted.
7	GOOD CONDITION - some minor problems.
6	SATISFACTORY CONDITION - structural elements show some minor deterioration.
5	FAIR CONDITION - all primary structural elements are sound but may have minor section loss, cracking, spalling or scour.
4	POOR CONDITION - advanced section loss, deterioration, spalling or scour.
3	SERIOUS CONDITION - loss of section, deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present.
2	CRITICAL CONDITION - advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.
1	"IMMINANT" FAILURE CONDITION - major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put it back in light service.
0	FAILED CONDITION - out of service; beyond corrective action.
99	Miscoded Data (Data that could not be evaluated by the WIM sensor)

These ratings are used to evaluate when action needs to be preformed (maintenance or renovation) in order to keep a stable condition for the bridge. Also another note worth mentioning is according to these condition ratings, cracking is always a fault in the bridges condition that is considered in evaluation. In the NBI criteria for evaluation of a bridges condition, the condition rating of 5, meaning fair condition, is the first instance in the criteria where a description of failure in the bridge is classified. In a fair condition rating cracking is present. Moreover, a fair condition rating looks for section loss spalling and scour. These other descriptions of damage that fall under a fair condition rating may also be analyzed by fracture mechanics. Section loss may be due to the damage of a piece of the bridges crack penetrating through the material thickness. Spalling and scour may be the result of a surface damage where the crack initializes from one surface and penetrates through the material ending another side of the same surface.

Moreover, action to maintain the bridges integrity is not held off until the bridge reaches a failed NBI condition rating equal to 0. Over the bridges service life there is usually a corrective maintenance action performed when the bridge condition reaches a fair or poor NBI Bridge condition rating. This can be interpreted as the bridges integrity is maintained by renovation or at least preventing cracks from expanding and continuously forming. Therefore, a comprehensive analysis on fracture mechanics and cracking may be helpful in producing improved models to calculate the remaining fatigue life of a bridge.

Cracking

For understanding of cracks in a bridge, a focus on fracture mechanics is necessary to obtain an understanding of how cracks can propagate in damaged material. There are three modes of how a crack may propagate. Mode 1 cracking models the elongation of a crack due to tension stresses. Figure 1 illustrates the force directions in which the forces are applied to the crack.

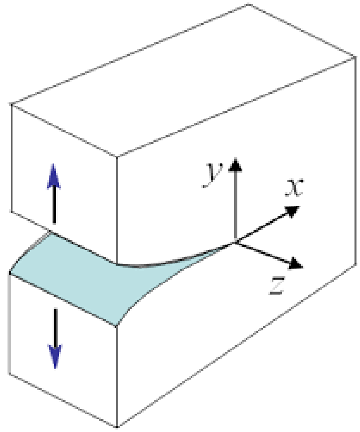

Figure 1: Fracture Mode I

The Forces in fracture mode I are perpendicular to the crack which creates the expanding of the crack by being pulled open. This case will be the most relevant case in this study.

Mode II cracking models the cracking continuation due to shearing stresses but in the axial direction. The extending damage of the material is created by a compressive force on one side of the crack and a tensile force on the opposite side. Figure 2 demonstrates this cracking model.

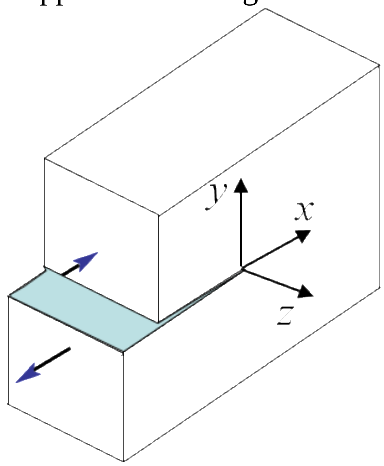

Figure 2: Fracture Mode II

Mode III cracking models the crack elongation due to shear stresses in the transversal direction. The extending damage of the material is created by a tearing force which is demonstrated in Figure 3.

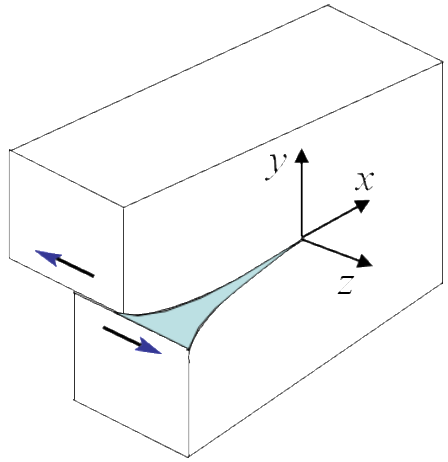

Figure 3: Fracture Mode III

The Forces in fracture mode II are parallel to the crack which makes the expanding by being torn apart.

Material Resistance

The fracture toughness quantifies the resistance of the material to brittle facture and defines the critical crack length.

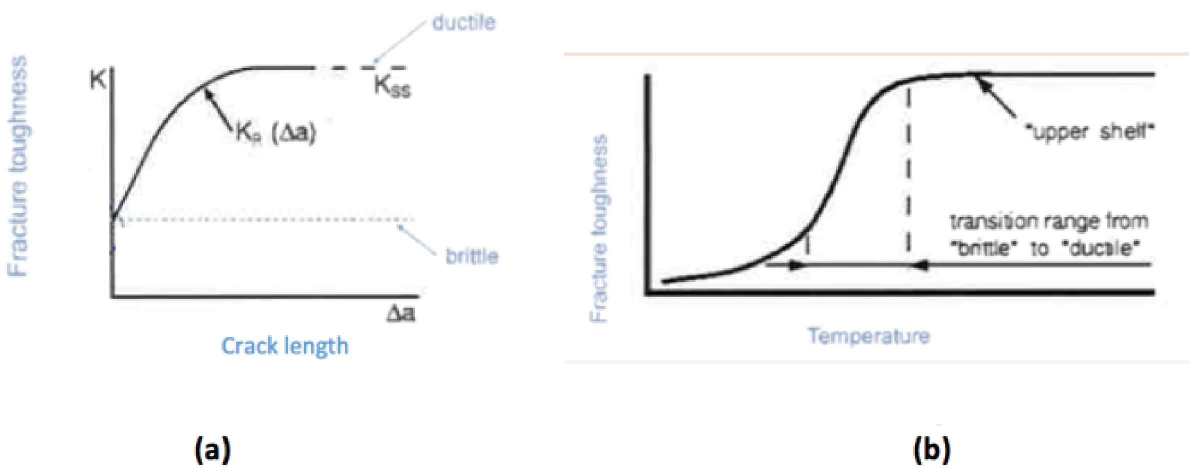

Figure 4: Fracture Toughness Variants [1]

Figure 4a displays the behavior of the materials fracture toughness when subjected to a variety of temperatures. The temperature will change the properties of the material. When the material is subjected to low heat it takes upon brittle properties. In the brittle state the fracture toughness is weak and has a relatively consistent fracture toughness. Because the fracture toughness is relatively constant under low temperatures, the brittle section is also referred to as the lower shelf. Similarly, after a certain range of higher temperatures the fracture toughness does not increase and this section is referred to as the upper shelf. In the range of the upper shelf the material is ductile. The ductile range has a higher fracture toughness, making it more difficult for the material to fracture. Moreover, in the state of ductile materials the member will show a more visible deformation before undergoing a crack failure. Between the upper and lower shelf or the brittle and ductile range of the materials variance due to temperature is the the transition range. The transition range is simply the range in which the materials temperature falls under the given range and is transitioning from brittle to ductile.

Figure 4b shows the influence of an increasing crack elongation to the fracture toughness. As the crack continues to propagate the crack tip will widen and will damage the material further. At the same time the resistance for the crack to continue to elongate will strengthen because the crack tip looses its piercing shape. Figure 5 describes the process in which the crack will continue to elongate.

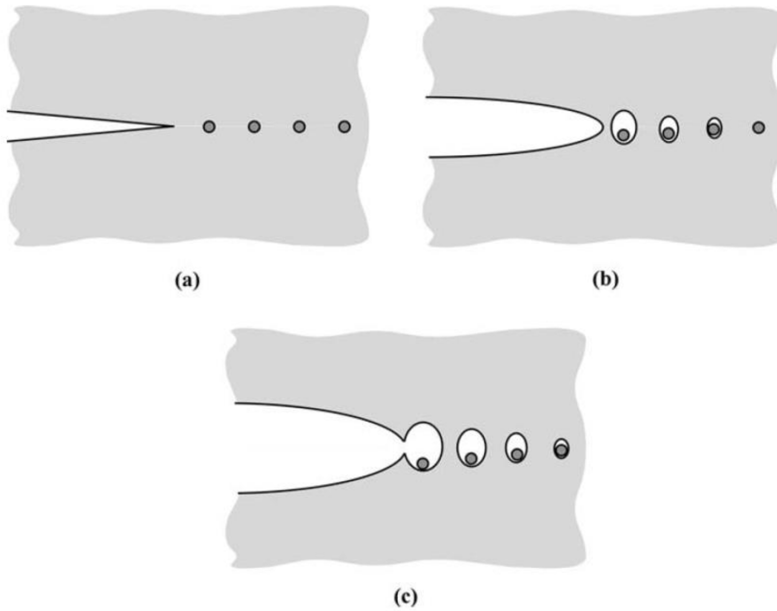

Figure 5: Crack Tip Elongations [2]

Figure 5a is a depiction of the void nucleation sprouting at the crack tip. The void nucleation is the beginning process for which the crack will expand and it creates the path in which the crack will continue to propagate. Figure 5b illustrates the next step in the process of how the crack will elongate. In this step the voids expand and the crack tips smoothens. The reason for the crack tip to smoothen is because it is also expanding along with the crack voids. Lastly, figure 5c shows the formation of the cracks of the voids. The crack will continue to expand until it has attached to all the expanded voids. The process will then repeat under a heavier load when another series of void nucleation sprout to make a path for the crack to continue to expand.

K-approach

The K approach is used in evaluating Linear Elastic Fracture Mechanics (LEFM). The term, K-approach, comes from the variable used to evaluate the stress intensity factor, K in the linear elastic range. This stress intensity factor, K, is equal to the fracture toughness of the limit state of brittle facture. Based on that the critical crack length $a_{critical}$ can be calculated. This report will use the K approach to evaluate fatigue crack growth on a bridge deck plate.

Fatigue Crack Growth

A bridge will undergo a series of repetitive dynamic loads from the vehicles that travel over it. The processes of loading and unloading of a series of loadings leading to a stress spectra is called fatigue. Fatigue damage on a bridge may consist of cracks, spalls or scours. The prospects of these damages may be better understood by an analysis of fatigue crack growth.

In 1961, P.C. Paris introduced the Paris Law formula, which is a relationship between the crack growth rate during cyclic loading and the range of the stress intensity factor. This relationship follows a power law formula but on a log-log plot it can be visualized as a linear graph.

Paris's Law gives a correlation between the stress intensity factor range and the sub-critical crack growth under fatigue stresses (for a crack length $a < a_{critical}$). This relationship is given by Equation 1 [2].

$$\frac{da}{dN} = C(\Delta K)^m \qquad\qquad Equation\ (1)$$

where $\frac{da}{dN}$ is the change in crack length over the change in cycle. This is also known as the the crack growth rate. The constants C and m are material properties of the cracking material obtained by experimental tests.

The correlation in the Figure 6, illustrates the behavior of the change in crack length as a dependent on the fraction intensity factor. Equation 1 or Paris's law expresses the behavior of the crack in region II.

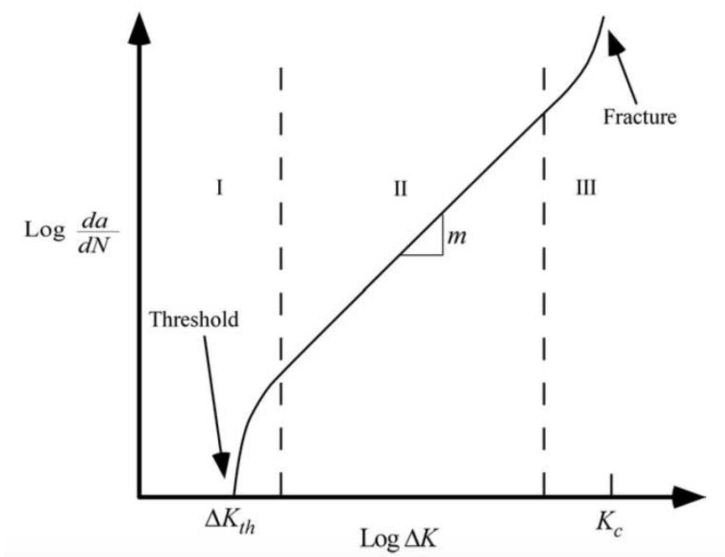

Figure 6: Typical fatigue crack growth in metals [2]

Equation 1 is modified by Klesnil and Lukas to account for the threshold of ΔK_{th}. ΔK_{th} is the threshold when cracking begins and it is obtained in material tests. Cracking does not occur until a certain stress level $\Delta\sigma$ is applied. Klesnil and Lukas's modified equation for the crack rate is shown in Equation 2.

$$\frac{da}{dN} = C(\Delta K^m - \Delta K_{th}{}^m) \qquad Equation\ (2)$$

The material properties C, m and ΔK_{th} are evaluated by laboratory tests. According to [4] (a German reference book on Fatigue Fracture Mechanics), table 7.3-31 tabulates the fatigue fracture mechanics steel properties, given in table 2.

Table 2: Fatigue fracture mechanics steel property [2]

Werkstoff	T [°C]	$R_{p0.2}$ [MPa]	R_K	C	m	ΔK_{th} [MPa $\sqrt{m}$]
26 CrNiMo 4	RT	366	0,1	2,51E-10	3,92	6,2 – 7,4

26 CrNiMo 4 is the particular steel alloy material which we will use for the crack propagation of the steel bridge deck due to the truck loading. Its fatigue cracking properties are shown in Table 2. ΔK_{th} will be evaluated at the lower range, 5.642 Kip*in$^{-3/2}$ (6.2 MPa$\sqrt{m}$)to obtain conservative results.

Analysis

Load model for road bridges for remaining fatigue life

The Federal Highway Administration (FHWA) classifies vehicles by its vehicle axle configuration. The vehicle types and classification is denoted in Figure 7 [5].

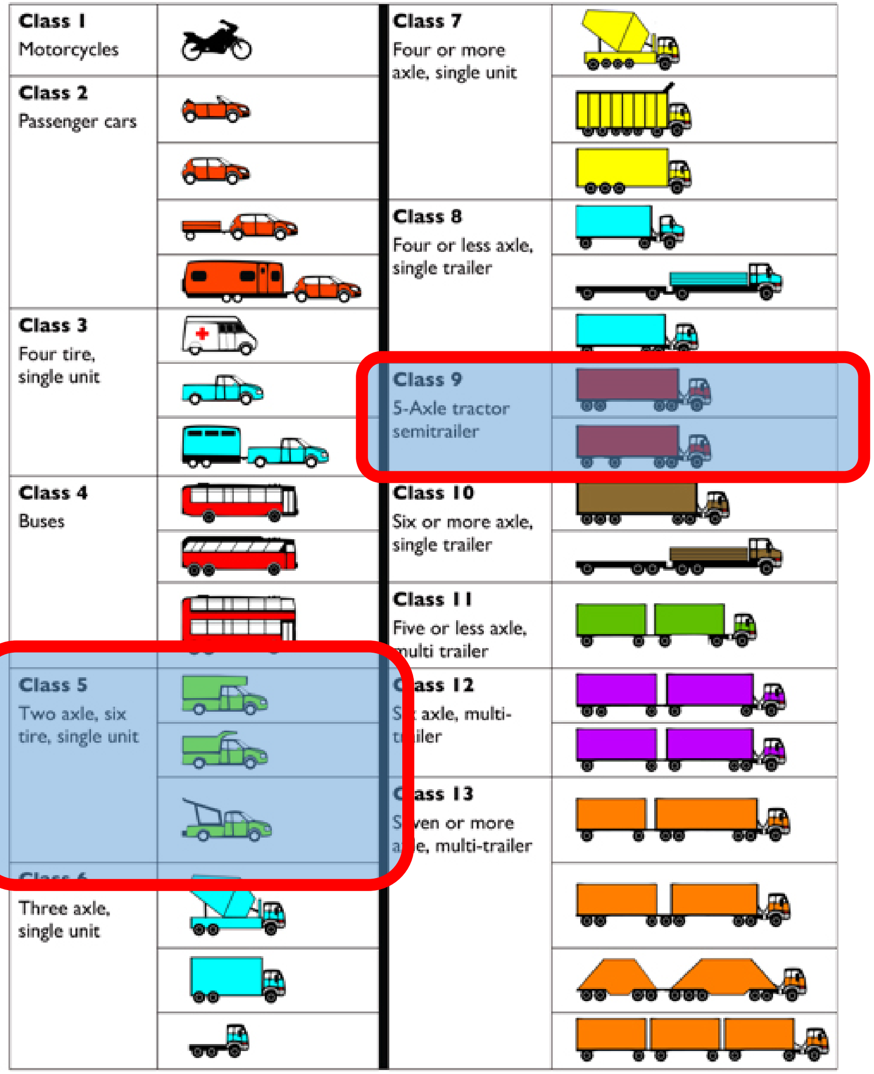

Figure 7: FHWA Vehicle Classification [5]

A sample orthotropic bridge is the Throgs Neck bridge in New York City over the East river. On an orthotropic deck, the spacing between the longitudinal stringers is very small to limit local bending stresses. The typical spacing of the longitudinal stringers on the Throgs Neck bridge deck is approximately thirty-nine and a half feet on center [7].

To evaluate the damage on an orthotropic bridge deck, a simulation of a series of trucks passing over the deck is evaluated to get the residual stress cycles, $\Delta\sigma_i$. The trucks that will be evaluated are trucks obtained from Weight in Motion (WIM) data on the Throgs Neck Bridge in 2005. Figure 8 presents a histogram of trucks by axle.

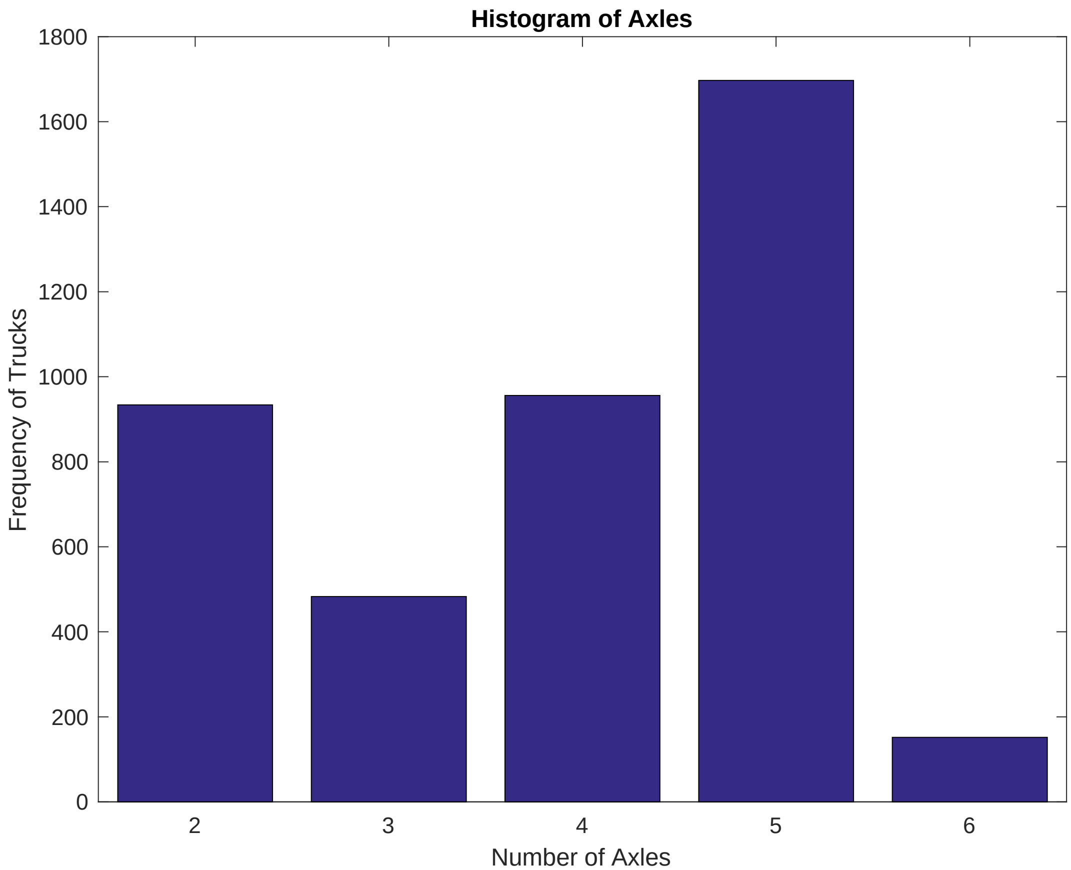

Figure 8: Histogram of Truck Frequency by Axle

According to the histogram in figure 8, the most frequent trucks are the trucks with five axles. These are often class 9 trucks. Trucks with four axles, the second most frequent driven truck types, are often categorized as class 8 truck types, are slightly more frequently driven than the trucks with two axles, or often categorized as class 5.

The number of trucks is one important parameter, besides the most important parameter, the axle weight. Another focus is to understand the amount of cargo transported by these vehicle types. Figure 9 illustrates the weight transported by each vehicle type.

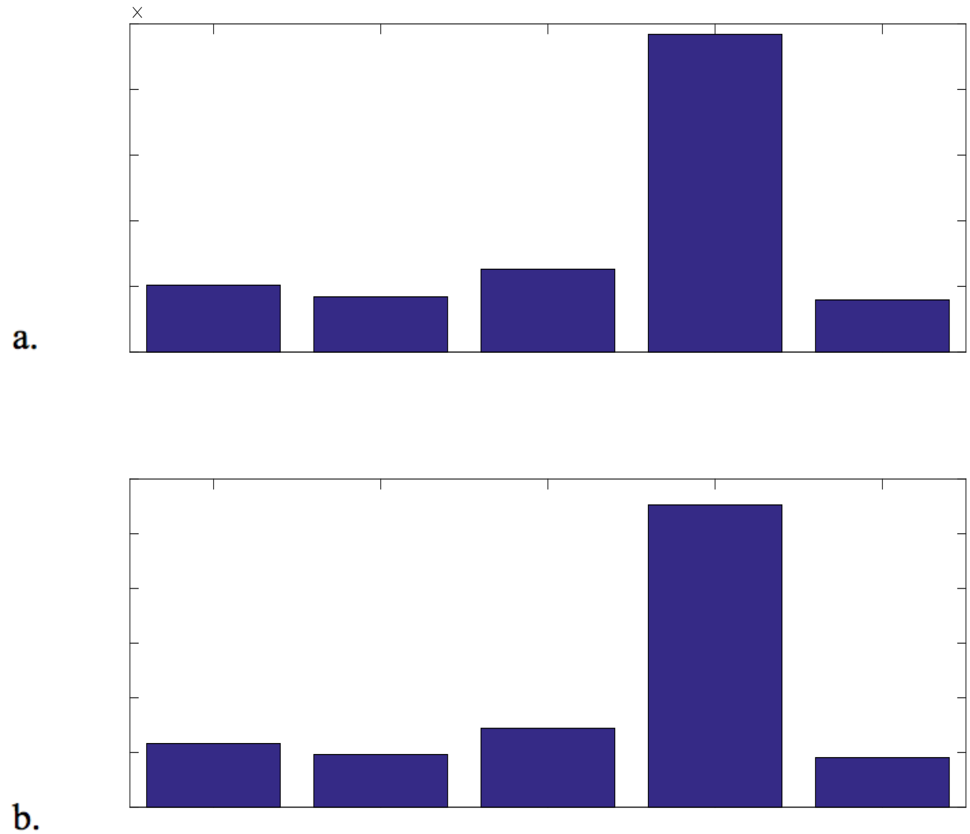

Figure 9: Histogram of Truck Weight (Kips) and percentage by Axle

From Figure 9a we see how the gross weight of each truck type resembles a relationship between the weight and number of trucks. However, comparing Figure 8 and Figure 9 shows that the relationship between the weight and number of trucks is not directly proportional. For example, the load per truck carried by a 5 axle truck (class 9 truck) is a lot more than the load carried by a 2 axle truck (class 5 truck). To be more specific the class 9 trucks carry 96.8 thousand kips of cargo across the bridge. The total number of class 9 category trucks that are analyzed through out the year is 1697 trucks. This means that on average for the year, each class 9 truck carried an average weight of 57 kips per truck. On the other hand, the total number of class 5 trucks are 934 and the total number of weight carried by class 5 trucks is 20.4 thousand kips. This means that on average for the year, each class 5 truck carried an average weight of 21.8 kips per truck. Figure 10 shows the comparison of the distribution of the average truck weight by each truck type. Figure 10 shows that the average truck weight of a class 9 truck (5 axle truck) is almost 3 times heavier than the average of a class 5 truck (2 axle truck). The average gross vehicle weight of the class 5 trucks is 21.82 kips and the average weight of the class 9 trucks is 57.04 kips.

To gain a better understanding of how much load each truck type carries within a year, Figure 9b plots a histogram of the trucks weight carried in proportion to the total load carried by all the trucks traveling over the bridge deck.

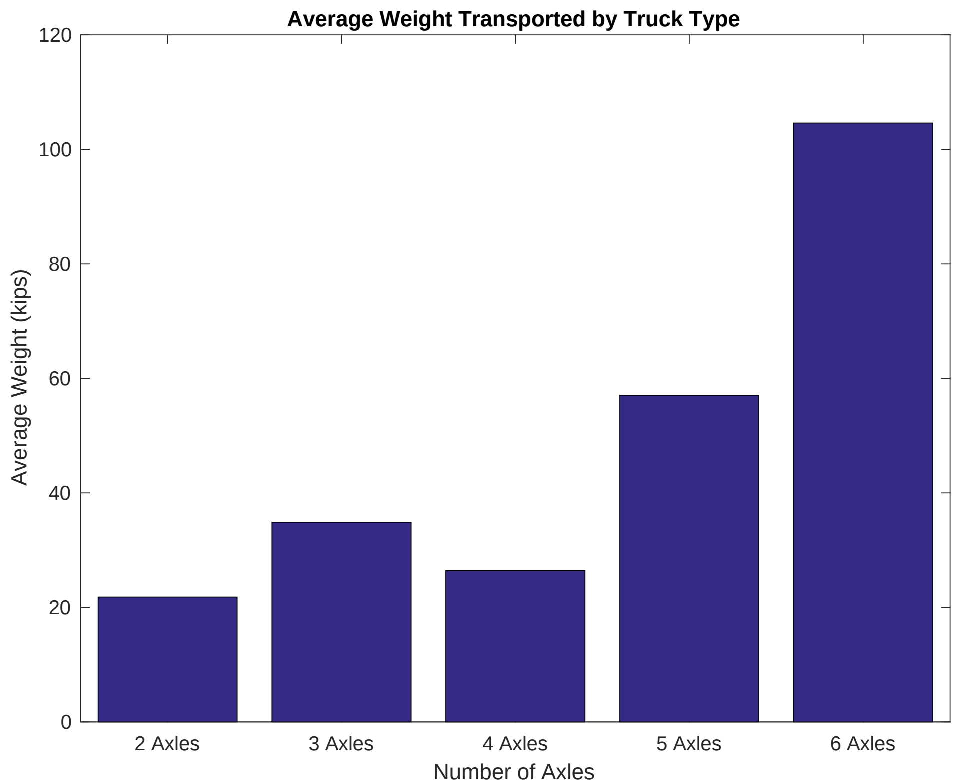

Figure 10: Average Truck weight by each Truck Type

In this report, I will focus on the 2 axle trucks (class 5 trucks) and the 5 axle trucks (class 9 trucks). Figure 11a and 11b show the distribution of the gross weight of the class 5 and class 9 trucks. This figures gives a better understanding of how much load each truck takes in comparison to the rest of the trucks of the same type. It also helps us to get a better understanding of what will be typical weights of the specified truck types. For example, it is very common to have class 9 trucks that weigh approximately 40 or 50 kips and class 5 trucks that weigh approximately 15 or 20 kips. There are almost 400 trucks that fall under the 40-50 kips range of the class 9 trucks and almost 250 class 5 trucks that fall under its maximum range of 15 -20 kips. Although there are twice as many tucks in the maximum range of the class 9 trucks as there is on the class 5 trucks, there is also twice as many class 9 trucks in the analysis. This means that weight distribution of the class 9 trucks and class 5 are very similar. The main difference between the class 5 and class 9 truck data is that the class 9 trucks hold a relatively higher weight than the class 5 trucks. Moreover, class 9 trucks have a higher weight range than the class 5 trucks.

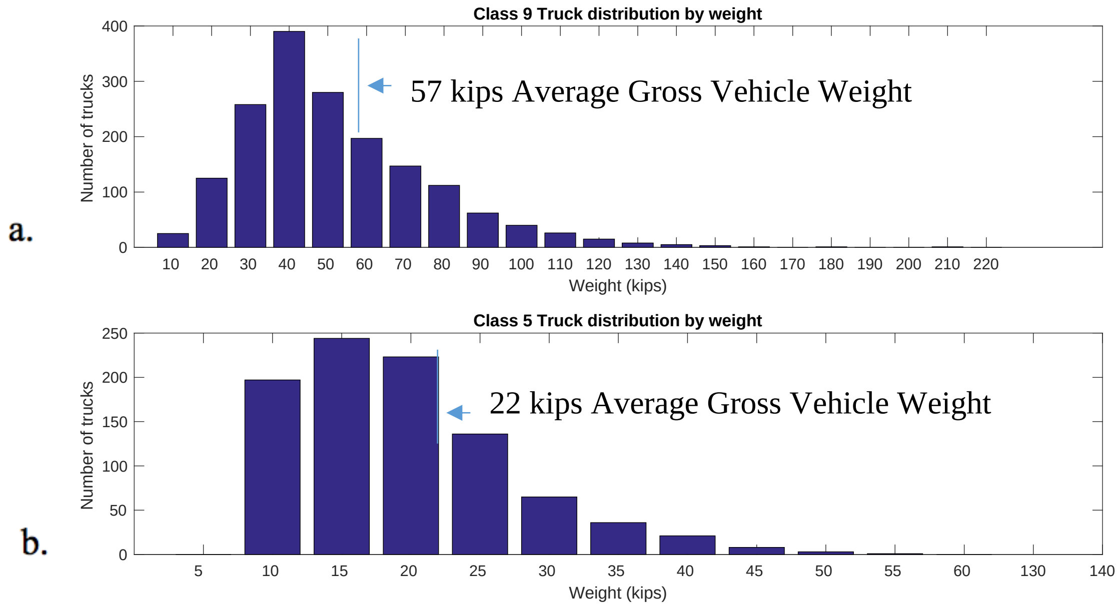

Figure 11: Class 9 and Class 5 Truck Weight Distribution

To grasp an understanding of the calculations, I will conduct a sample computation of the damage inflicted by a random truck from the class 9 and class 5 database used to evaluate the damage on the Throgs Neck Bridge. The class 9 sample truck will be used to conduct sample calculations and its configuration is shown in Figure 12a and the class 5 sample truck is shown in figure 12b. This configuration shows the axle spacing and the loading of each axle.

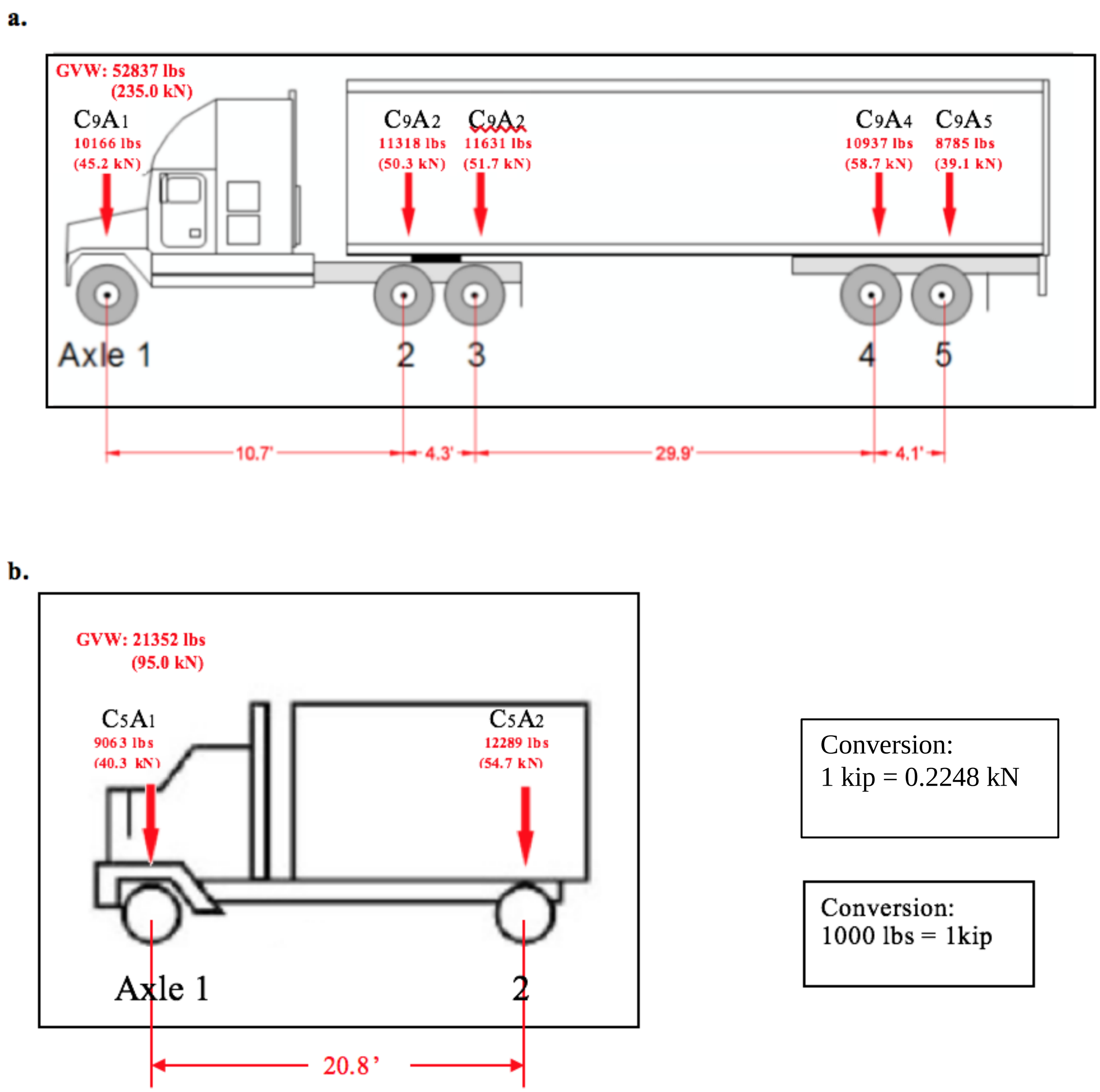

Figure 12: Sample 5 Axle Truck Configuration and Sample 2 Axle Truck Configuration

The 5-axle sample truck presented in Figure12a is a class 9 tuck type. The 2-axle sample truck presented in Figure12b is a class 5 tuck type. The two sample truck specimens in Figure 12 were selected because they both are similar to the average gross weight of their respective truck classification, which will help give a good representation of the general configuration of their respective classes. According to Figure 11a, the average gross vehicle weight in the WIM database of class 9 trucks is 57 kips while the class 9 sample truck shown in Figure 12a, has a gross vehicle weight of approximately 53 kips. Recall from Figure 12 conversion that 1000 pounds equates to 1 kip. From Figure 11b, the average gross vehicle weight of a class 5 truck is 22 kips, while the gross vehicle weight of the class 5 sample truck in Figure 12b is 21 kips. Therefore, the gross vehicle weight of the sample trucks is closely represented by the respective class's average gross vehicle weight in the WIM database. Moreover, there are different variations of axle loads on both truck samples will vary depending on the way the cargo is packed and distributed on the truck. From the sample specimen trucks the distribution of the load of the class 9 truck is mainly distributed evenly through the front and center while in the class 5 truck the load is mainly distributed on the back end of the truck. This may cause some axles to carry heavier loads than others which will consequently have a larger impact on the deterioration of the bridge deck plate.

The loads are evaluated as concentrated point loads. However, the load is distributed to the deck over the contact area of the tires. Therefore, it is imperative to conduct an analysis of the tires contact area to understand how the loads are transferred to the deck.

Tire Contact Area Analysis

An Analysis on contact tire area can be created using a study by Enginebasics [3]. In the study by Enginebasics [3], Enginebasics [3] tabulates the results of contact patch length after increasing the loads at different increments under a 28-psi pressured tire. The results are tabulated in Table 3.

Table 3: Load vs Contact Patch Length [3]

Load [lbs]	Contact Patch Length [in]	Area [sq in]	Contact Patch Width [in]
70.55	1.94	23.63	12.21
119.05	2.81	34.31	12.21
171.96	3.29	40.11	12.21
227.08	3.76	45.84	12.21
282.19	4.12	50.31	12.21
332.9	4.50	54.97	12.21
388.01	4.77	58.21	12.21
443.13	5.05	61.77	12.24
498.24	5.37	65.59	12.21
553.36	5.52	67.42	12.21
608.48	5.88	71.78	12.21
663.59	6.18	75.47	12.21
718.71	6.31	77.05	12.21
771.62	6.50	79.36	12.21
828.94	6.72	81.97	12.21
881.85	6.80	83.06	12.21
936.96	7.09	86.59	12.21
992.08	7.26	88.64	12.21
1047.2	7.43	90.63	12.21
1102.31	7.56	92.26	12.21
1157.43	7.77	94.80	12.21
1210.34	7.92	96.66	12.21
1267.66	8.09	98.77	12.21
1320.57	8.21	100.26	12.21

From Table 3 we see that as the load increases the width contact patch stays the same. Moreover, the contact patch length will increase as the load increases. To get an understanding of the behavior of the relationship between the load and the contact patch length, we should analyze the two factors in a plot. After plotting the results and fitting the trend of the data to a logarithmic regression, we obtained the plot shown in Figure 13.

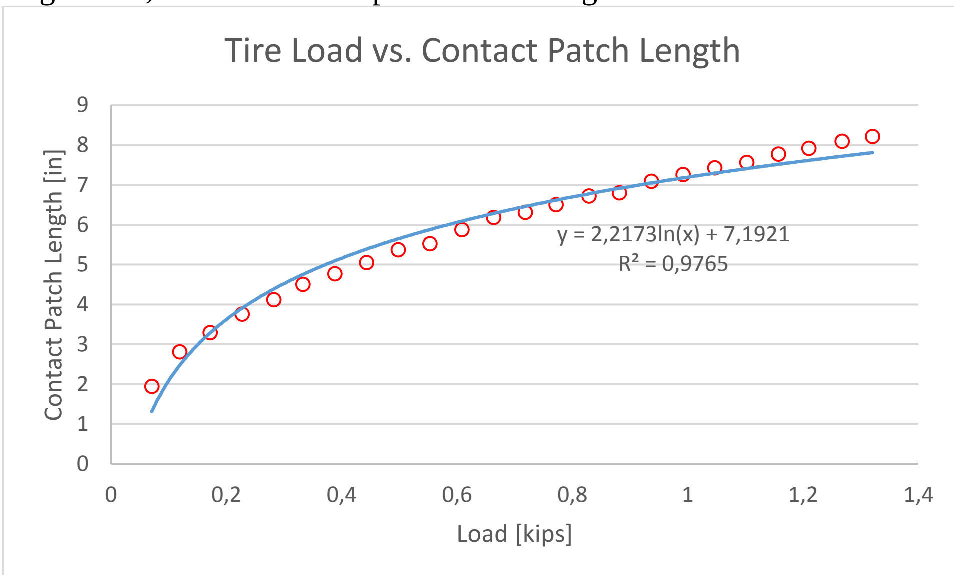

Figure 13: Logarithmic Regression of Tire load vs Contact Patch Length

The R^2 value of the logarithmic regression is 0.97647. This means that a logarithmic regression would be a fairly accurate fit for the load vs. contact patch length data. Because there is a logarithmic relationship between the contact patch length and the load, the contact patch length can be obtained by using the logarithmic trend in Figure 13 to find the contact length in inches from the axle load in kips.

Assuming that the load is distributed uniformly over the contact patch area we can evaluate the distributed axle load over the contact patch area. After calculating the contact patch length, we are able to obtain the distributed load over the contact patch area.

Typically, over the steel deck of the orthotropic deck there is an asphalt layer or wearing layer that protects the bridge deck from direct contact with the vehicle. The load is distributed to the deck on a 1:1 scale with the thickness of the deck or a 45-degree angle as shown in Figure 14.

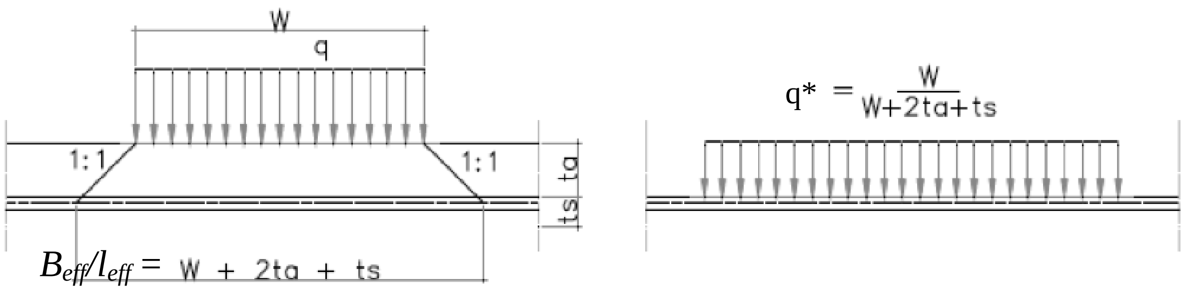

Figure 14: Load dispersal simplified [Eurocode 1 Part-2]

Figure 14 shows how the distributed load over the thickness of the asphalt is distributed to the steel deck. As the truck loading on the asphalt gets distributed to the steel deck, the load is spread more widely along the steel deck surface. Since the distributed load is spread over a longer span, the distributed loading is less concentrated. Based on this load model curve the steel deck is modelled for stress analyses.

Damage Analysis

The loading of the axial load of a vehicle on the Bridge deck creates bending stresses on the bridge deck. Calculations for the sample truck shown in Figure 12 will be conducted to show the process of calculating the fatigue damage and will then be iterated by a Matlab code to reiterate a scenario of class 9 trucks from the given data set and then another scenario of class 5 from the given data set of trucks. Based on this load curve, the steel deck is modeled for the stress analysis.

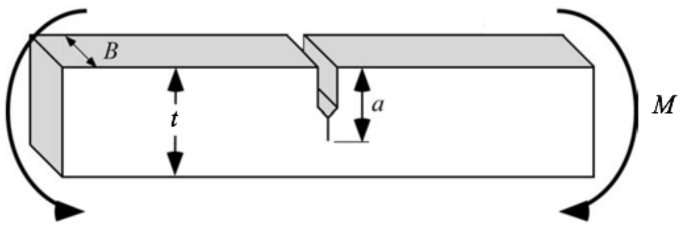

Figure 15: Cracking Analysis of 2-Dimensional Deck Plate in Bending[2]

Figure 15 is a model of a 2-Dimensional plate in bending. When a distributed load is loaded on the deck plate it will be equivalent to a plate in bending. A distributed load, q^* distrbuted over a length, l will have the equivalent bending moment, M of

$$M = \frac{q^* {l_{eff}}^2}{8} + \frac{q^* l_{eff} * (s - l_{eff})}{8} \qquad Equation\ (3)$$

where q^* is the uniformly distributed load along the effective length of the axle tire,

l_{eff} is the effective length of the axle tire and

s is the span between the two adjacent stringers that the deck lies above (39.5' [7]).

Equation 3 is equated by solving for the maximum moment on an equivalent model that represents the similar loading of a truck axle on the bridge deck. The equivalent model is represented in Figure 16.

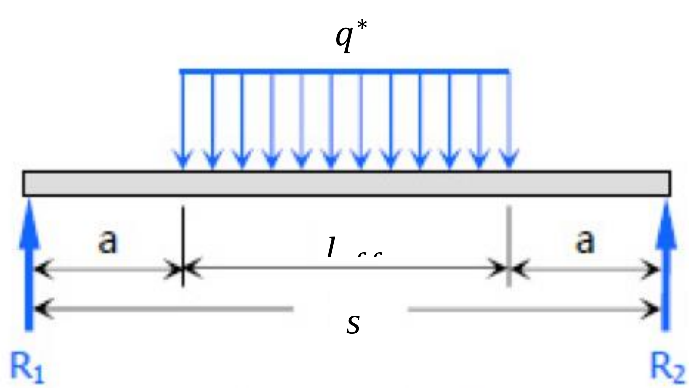

Figure 16: Equivalent loading model of a truck axle on the Bridge deck

The stress resulting from the deck is calculated as:

$$\sigma = \frac{6M}{{t_e}^2 B_{eff}} \qquad Equation\ (4)$$

where t_e is the depth of the plate and

B_{eff} is the effective width under the tire in which the axle load is distributed to.

Crack elongation is calculated using the stress as obtained above in equation 2 and the shape factor which denotes the behavior or the crack elongation based on the geometric properties of the plate stimulated in the crack propagation.

ΔK is obtained by the change in intensity factor or $K - K_{min}$. The stress intensity factor (kips/in$^{3/2}$) is evaluated by Equation 5 [2].

$$K = \sigma * \sqrt{\pi * a} * f(r) \qquad Equation\ (5)$$

where a (in) is the crack length.

σ (kips/in^2) is the stress on the plate which can be obtained by Equation 4 and

f(r) is the shape factor as a function of *r*.

r is the ratio between the crack length to the thickness of the plate.

K is calculated in Kips*in$^{3/2}$

The shape factor for a plate a crack along the length as shown in figure 15 is calculated by equation 6 [2].

$$f(r) = \frac{6\sqrt{2\tan\left(\frac{\pi r}{2}\right)}}{\cos\left(\frac{\pi r}{2}\right)}[0.923 + 0.199\left\{1 - \sin\left(\frac{\pi r}{2}\right)\right\}^4] \qquad Equation\ (6)$$

The single edge notched bend specimen loaded in bending closely resembles the deck loading of an isotropic deck under a truck axle loading. The fracture intensity for the single edge notched bend specimen loaded in bending can be calculated by Equation 5 where Equation 6 is used to solve for the shape factor.

Damage Calculations

Obtaining the stress intensity factor, K, for each loading is the initial stage in the analysis to understanding the crack rate per loading cycle. The next stage is to compare the stress intensity factor to the threshold stress intensity factor to understand the rate at which the one inch deck plate will crack under each consecutive loading. Sample truck specimen in Figure 12 will be used to demonstrate the calculations of the fracture of the deck plate.

Step 1: Find tires actual applied distributed load using Tire Contact Area Analysis

The first loading of the class 9 specimen truck is 3040 lbs (3.04 kips). The tire weight is distributed along the length and width of the tire. The truck contact tire width is 12.21 inches. The tire contact length is obtained by using the logarithmic trend curve (Equation 7).

$$y = 2.2173ln(x) + 7.1921 \qquad Equation\ (7)$$

where y is the tire contact length (inches) and
x is the equivalent tire load (kips)

Using Equation 7 to calculate the contact length for the first axle is shown below.

$$actual\ contact\ length = 2.2173 \ln(12.16) + 7.1921 = 12.73\ inches$$

The tire load is not directly in contact with the deck. There is usually a three-inch-thick layer of wearing surface between the tires and the deck. Using the load dispersal concept from Figure 14, an additional term must be added to the actual contact length.

$$Projected\ Contact\ Length = W + 2ta + ts = 12.73 + 2 * 3 + 1 = 19.73\ inches$$
$$Projected\ Contact\ Width = W + 2ta + ts = 12.21 + 2 * 3 + 1 = 19.2\ inches$$

This contact length is the length of the distributed load that is projected on to the deck plate. Moreover 3040 pounds is distributed over the projected contact are. Therefore, distributed load is 14.9 pounds per sq.-inch (3040 pounds / [16.7 inches*19.2 inches]).

Table 4 shows the projected contact length and distributed loadings of the consecutive axles of the class 9 and 5 truck sample specimens in Figure 12.

Table 4: Class 9 truck sample truck projected contact length and distributed loading

Axle label	Axle Weight (lbs)	Projected Contact Length (inches)	Projected Width Length (inches)	Distributed load (lbs/in^2)
C_9A_1	10166	19.33	19.21	525.81
C_9A_2	11318	19.57	19.21	578.27
C_9A_3	11631	19.63	19.21	592.43
C_9A_4	10937	19.50	19.21	560.98
C_9A_5	8785	19.01	19.21	462.12
C_5A_1	9063	19.08	19.21	475.01
C_5A_2	12289	19.75	19.21	622.08

Step 2: Solve for the stress cycle due to each passing axle exerts on the deck.

The distributed load acting on the deck creates tensile forces on the bottom of the deck. If the crack initializes at the lower end of the deck the crack will continue to propagate as a mode 1 fracture. Recall, mode 1 fracture is when the fracture is created when the forces are perpendicular to the crack and are pulling the crack apart. The stress cycle created by the applied distributed axle loading will pull apart the crack extending, the crack until failure. The applied axle distributed load can be converted to equivalent bending moments, based on the deck plate's stress cycle. This can be visualized in Equations 3 and 4. Below is the calculations to obtain the stress exerted from the first axle.

$$M = \frac{525.81 * 16.66^2}{8} + \frac{525.81^* 16.66 * (39.5ft * 12\frac{in}{ft} - 16.66)}{8} = 602{,}335.5\ \ lb * in$$

$$\sigma = \frac{6M}{t^2} = \frac{6 * 602{,}335.5}{1^2 * 19.21} = 188{,}130\ psi * \frac{1\ kip}{1000\ lbs} = 188.13\ ksi$$

Table 5 tabulates the stresses calculated from each axle of each sample truck in Figure 12.

Table 5: Stress on the deck caused by each axle of the sample trucks in Figure 12.

Axle label	Axle Weight (kips)	Stress in the Deck Plate (ksi)	Stress in the Deck Plate (MPa)
C_9A_1	10.166	188.13	1297.12
C_9A_2	11.318	209.45	1444.11
C_9A_3	11.631	215.24	1484.05
C_9A_4	10.937	202.40	1395.50
C_9A_5	8.785	162.58	1120.92
C_5A_1	9.063	167.72	1156.39
C_5A_2	12.289	227.42	1568.01

Step 3: Find the stress intensity factor for each axle loading

Recall the stress intensity factor equation, Equation 5, and shape factor equation, Equation 6. The next step includes solving for the stress intensity factor using the shape factor equation. After obtaining the stress intensity factor, it must be compared to the fracture toughness, K_c, to determine if the applied stress will cause the material to fracture.

$$f(r) = \frac{6\sqrt{2\tan\left(\frac{\pi r}{2}\right)}}{\cos\left(\frac{\pi r}{2}\right)}\left[0.923 + 0.199\left\{1 - \sin\left(\frac{\pi r}{2}\right)\right\}^4\right]$$

The shape factor is an equation dependent on the ratio of the original crack of the plate to the thickness of the plate as shown above. However, in the beginning of the evaluation there is no initial fracture. Therefore, we will assume an initial crack of 0.05 inches as manufacturing error. The shape factor evaluated with a crack of 0.5 inch to 1 inch deck ratio is 2.55.

$$f(0.05) = \frac{6\sqrt{2\tan\left(\frac{\pi * 0.05}{2}\right)}}{\cos\left(\frac{\pi * 0.05}{2}\right)}\left[0.923 + 0.199\left\{1 - \sin\left(\frac{\pi * 0.05}{2}\right)\right\}^4\right] = 2.55$$

The stress intensity factor is calculated by Equation 5. As calculated in Table 5, the stress evaluated by the first axle of the sample truck is 102.92 psi.

$$K = \sigma * \sqrt{\pi * a} * f(r) = 188.13\ ksi * \sqrt{\pi * 0.05} * 2.55 = 189.89\ ksi\sqrt{in}$$

The stress intensity factor for each axle on the sample specimen truck are tabulated in Table 6.

Table 6: Stress intensity factor for each axle load

Axle label	Axle Weight (kips)	Stress intensity factor with 0.05 in crack length [ksi√in]	Stress intensity factor with 0.05 in crack length [MPa√m]
C_9A_1	10.166	189.89	208.65
C_9A_2	11.318	211.40	232.30
C_9A_3	11.631	217.25	238.72
C_9A_4	10.937	204.29	224.48
C_9A_5	8.785	164.09	180.31
C_5A_1	9.063	169.28	186.02
C_5A_2	12.289	229.54	252.23

The next step compares the stress intensity factor to check if the critical crack length is reached.

Step 4: Solve for crack length extension

First, the change in stress intensity factor obtained from each axle loading must be compared to the threshold material properties of the the deck to understand the fatigue fracture that the loading has on the deck plate.

Referring to Figure 6, ΔK_{th} is the minimum change in stress intensity required for a crack to elongate. The ΔK_{th} for the deck plate that we are evaluating is 5.642 ksi√in (6.2 MPa√m). If the change in stress intensity factor due to each axle is greater than the threshold ΔK_{th} stress intensity factor, the axle will cause the crack to elongate.

Equation 2, Klesnil and Lukas' equation, will be used to evaluate the crack extension for each crack cycle. A crack cycle is the loading and unloading of each axle. The Klesnil and Lukas equation uses the term ΔK. ΔK is based on the actual crack length and the sequence in which the loads are applied. This is important because the order of the loading matters. If the sequence of loadings were to gradually increase the crack will gradually elongate. However, if the sequence of the loadings had heavier loadings first, the crack on the deck plate will extend more rapidly.

The crack extension for the second axle on the class 9 sample truck specimen is calculated below. Note the Klesnil and Lukas equation is an empirical formula equated by units of fracture toughness in MPa√m. The conversion from inches to meters is one inch is equal to 0.0254 meters.

$$\frac{da}{dN} = C(\Delta K^m - \Delta K_{th}{}^m) = 2.51 * 10^{-10} * ((208.65 - 0)^{3.92} - 6.2^{3.92}) * 0.254$$
$$= 7.88 * 10^{-3} in$$

The stress intensity factor used to evaluate ΔK for each axle and the crack length per cycle is evaluated in Table 7 in the order of the axle order crossing over the deck plate.

Table 7: Evaluation of crack Extension from Sample Specimen Truck

Axle label	Crack Cycle	Axle Weight (kips)	Stress Intensity Factor [ksi√in]	Minimum Stress Intensity Factor [ksi√in]	Stress Intensity Factor [MPa√m]	Minimum Stress Intensity Factor [MPa√m]	Crack Extension (inches)
C_9A_1	1	10.17	189.89	0.00	208.65	0.00	7.88E-03
C_9A_2	2	11.32	211.40	189.89	232.30	208.65	1.54E-06
C_9A_3	3	11.63	217.25	189.89	238.72	208.65	3.96E-06
C_9A_4	4	10.94	204.29	189.89	224.48	208.65	3.12E-07
C_9A_5	5	8.79	164.09	189.89	180.31	208.65	0.00E+00
C_5A_1	1	9.06	169.28	0.00	186.02	0.00	5.02E-03
C_5A_2	2	12.29	229.54	169.28	252.23	186.02	8.76E-05

Step 5: Repeat of axle passing

Lastly, the calculations for calculating the cracking damage of the deck plate is repeated for the next Truck that passes of the deck plate. As more and more trucks pass over the bridge deck plate, the crack will extend. The increase in the extension of the crack, increases the stress intensity factor. As the stress intensity factor increases so will the rate at which the crack develops along the deck plate.

Appendix B: Fatigue Analysis Code is a Matlab code that simulates the cracking of the deck plate as the trucks from the Throgs Neck Database were to be loaded on the deck plate. The database expands over a year and the simulations calculates the life of the bridge deck plate under the assumption that the traffic volume will follow the same pattern each year. Moreover, the Appendix B: Fatigue Analysis code creates two scenarios. The first scenario uses the class 9 trucks and magnifies the gross weight volume of class 9 trucks to reach the total volume of trucks in the Throgs Neck database. The second scenario mirrors the first scenario but magnifies the total gross vehicle weight volume of the class 5 trucks to the gross vehicle weight volume of trucks in the entire Throgs neck database. Therefore, in both scenarios there will be an identical gross weight of vehicles passing over the bridge in the year. However, the scenario that fails first will carry less weight over the bridge because the scenario that last longer will have more time to carry more weight over the bridge.

Results

The simulation of trucks conducted through the Matlab code (Appendix B: Fatigue Analysis Code) evaluated truck data of the cargo that travels on the Throgs Neck Bridge. The simulation consisted of two scenarios. The first scenario depicts a case were the entire selection of class 9 trucks from the database are used to transport the cargo over the bridge and the second scenario depicts a case were the entire selection of class 5 trucks are used to transport the cargo over the bridge until the bridge deck plate failed. In both scenarios, the rate of cracking and the amount of cargo transported was recorded during the simulation over the life span of the bridge deck plate.

The results are illustrated in the plots of figure 17.

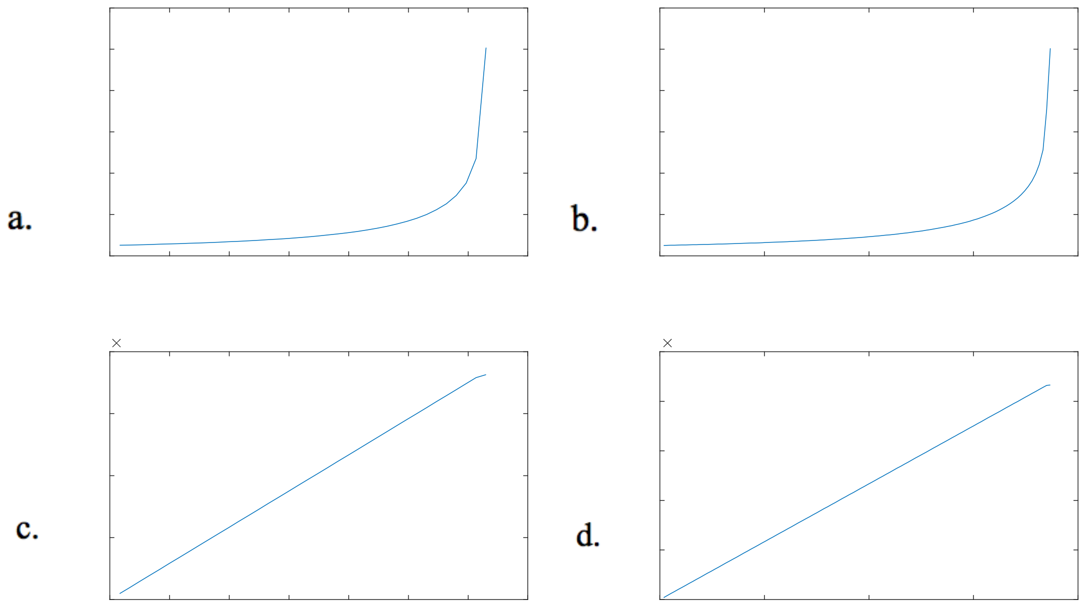

Figure 17: Damage incurred and cargo transported by Class 5 and Class 9 Trucks

According to Figure 17a and 17b the cracking of the deck occurs at an exponential rate. Figure 18 gives a more visual representation of the comparison of the fatigue life span of the bridge deck plate in both scenarios.

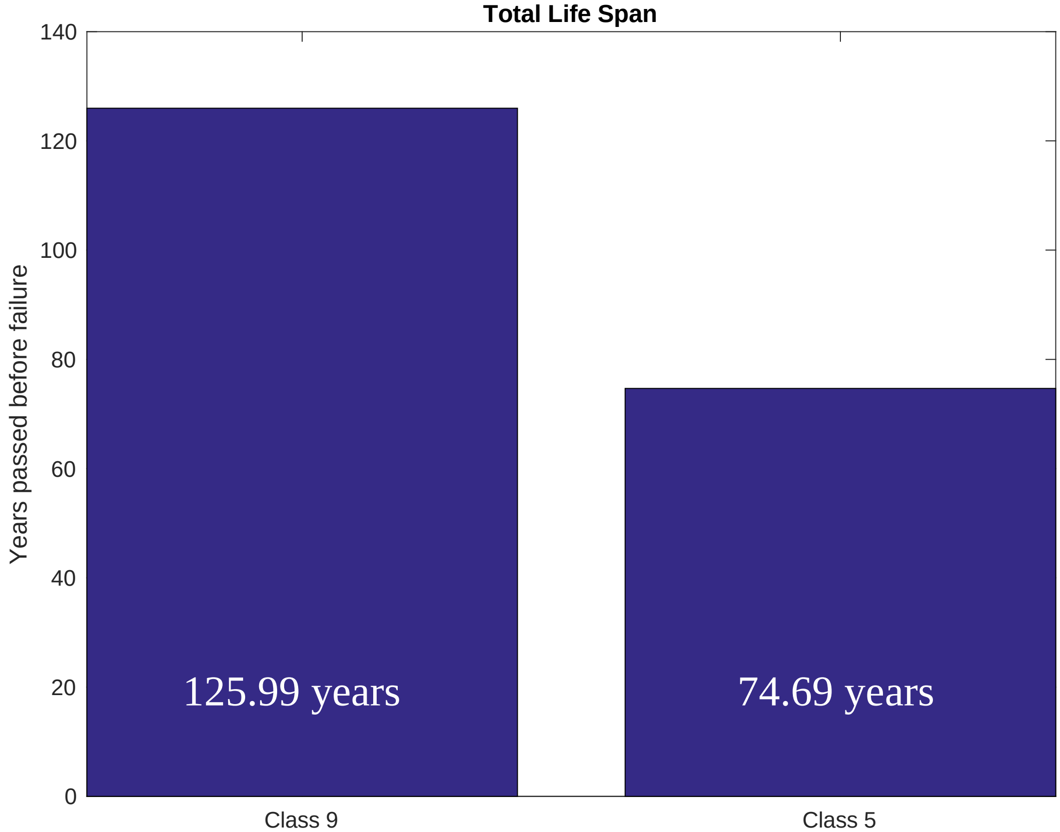

Figure 18: Comparison of fatigue life time under Class 5 (trucks with 2 axles) and Class 9 (trucks with 5 axles) load case scenario

The fatigue life time of the bridge deck plate under class 9 scenario is 125.99 years. The fatigue life span of the bridge deck plate under class 5 scenario is 74.69 years. From the results, the age of the bridge deck plate will last a little less than two-thirds the fatigue life time when using the class 5 scenario over the class 9 scenario. Moreover, the analysis conducted evaluated the fatigue life time of the bridge deck without the influence of maintenance of the cracks or replacement of the bridge deck plate. Nevertheless, we learn valuable information on how the fatigue life time of the bridge deck plate influenced by fatigue damage.

The second set of results of the two scenarios focused on the amount of cargo transported before the bridge deck plate failed. Figure 17c and 17d shows that the amount of cargo follows a linear curve. The reason for this is the assumption that each year the same amount of cargo will be loaded, as the cargo analyzed in the WIM data. In reality there may be an increase of cargo per year to reach the demands of the population growth. Nevertheless, the total amount of cargo transported by the class 9 truck scenario is approximately 21.78 million kips and the total amount of cargo transported by the class 5 truck scenario is approximately 12.99 million kips. Therefore, the class 9 truck scenario was able transport approximately 8.79 million kips more of Cargo than the class 5 truck scenario. Figure 19 gives a visual representation of the comparison between the amount of cargo transported by the class 9 Truck scenario versus the amount of cargo transported by the class 5 Truck scenario.

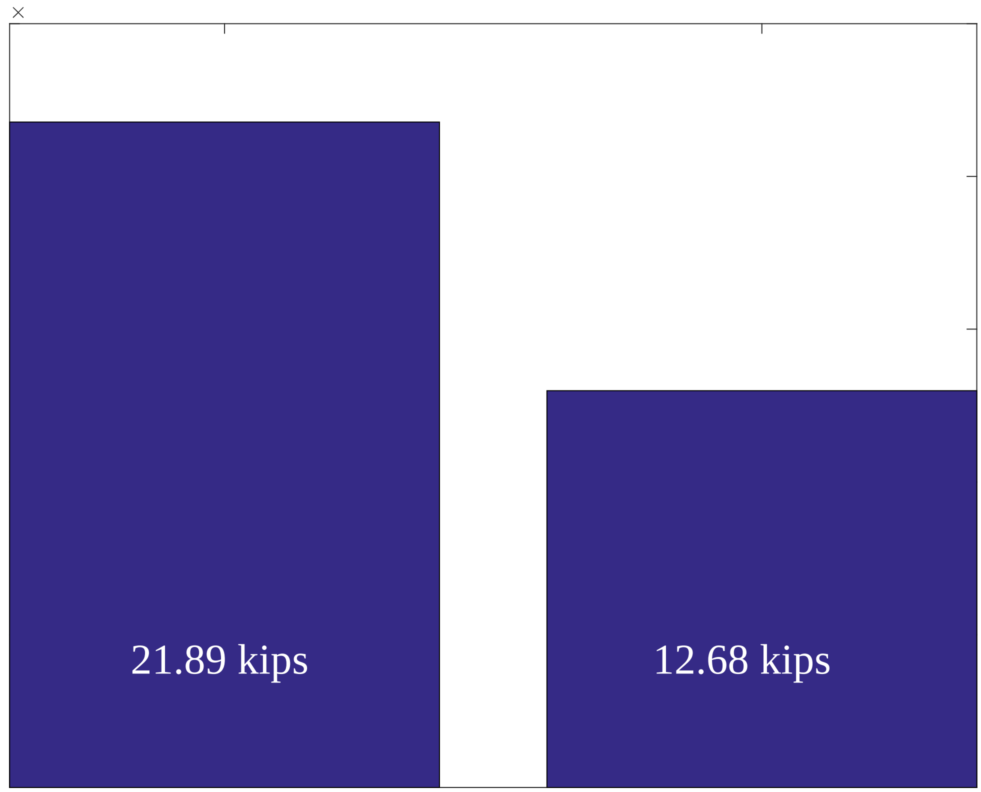

Figure 19: Comparison of total transported cargo under Class 5 and Class 9 load case scenario

The number of trucks in each scenario was scaled up to transport the total amount of cargo transported on the Throgs Neck Bridge. This means that the total weight for each scenario are identical. This is done to clearly distinguish the effect of the configuration of the trucks because there are more class 9 trucks in the WIM database and not scaling the two scenarios would make it difficult to compare meaningful results. The scaling is calculated by magnifying the original total weight of the trucks in the class scenario to the total weight in the year. Recall from Figure 9, the total weight of all the trucks in the WIM database is 175 thousand kips. There is a total gross weight of 20.4 thousand kips in the class 5 scenario and 96.8 thousand gross weight in the class 9 scenario. For the gross weight of the class 5 trucks in the class 5 scenario to be scaled up to the total gross weight in the WIM data the class 5 gross weight must be multiplied by 8.5957 (175 thousand kips /20.4 thousand kips). Similarly, the class 9 gross weight must be multiplied by 1.8097 (175 thousand kips /96.8 thousand kips).

The WIM Data has a total of 4222 Trucks along all 6 lanes. Three of the lanes are in the Northbound direction and the other three are in the southbound direction. The WIM data does not distinguish which trucks are captured in which lane. Therefore, this study will assume the truck volume is distributed evenly across all six lanes. This means that when calculating the damage on each lane we will only consider a sixth of the trucks in the magnified volume of gross truck weight as the gross truck weight in the year.

The average number of weight transported per year in both scenarios is approximately 0.175 million kips. If we divide the total amount of cargo transported by the fatigue life time of the bridge deck plate of each case scenario, we will obtain the average weight transported per year.

The stress cycles in the deck plate are obtained play an important role in calculating the fatigue life of the deck plate. The stresses in the deck plate influence the stress intensity factor which dictates the elongation of the crack in each cycle. Figure 20 plots the stress spectra of both the class 9 and class 5 scenario.

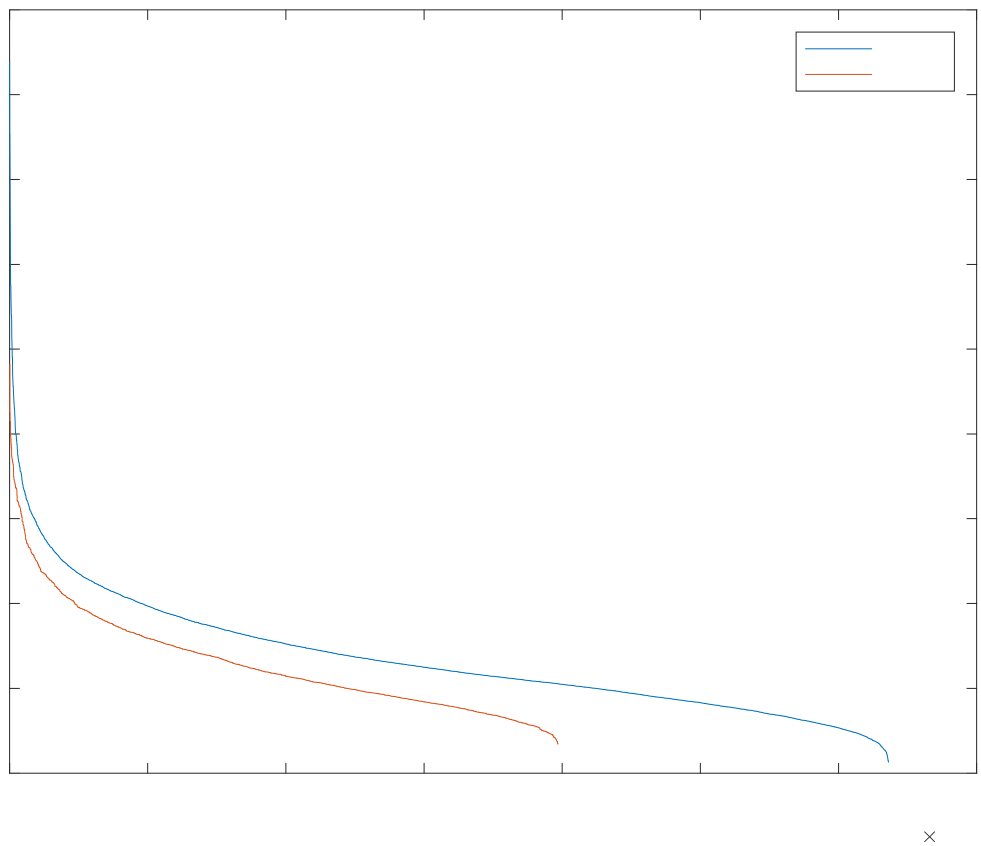

Figure 20: Class 9 and Class 5 stress spectra

To obtain the Stress Spectra stresses retrieved from the truck loadings were sorted in descending order. After plotting the stresses throughout the lifespan of the deck from each loading scenario, we see a slight increase in stress from the class 9 trucks over the class 5 Trucks throughout the stress spectra. However, on the very left the stress spectra, class 5 starts off higher on the stress spectra. The quick change in stress on the stress spectra on the class 5 curve allows the class 5 scenario to deteriorate quicker under the fatigue. Figure 21 shows the distribution of the by axle weights. Note that class 5 and class 9 scenarios are fairly similar in axle weight distribution. However, the number of heavier axles are slightly higher in the class 5 model than the class 9 model.

The results are very interesting because the class 9 truck scenario was able to transport more load than the class 5 scenario and the class 9 bridge deck plate lasted longer than in the class 5 scenario. To add to the observation, there is a greater cumulative stress impact on the bridge deck from the class 9 trucks than the class 5 trucks. Yet the slight increase of stress on the maximum stresses had a greater impact in lowering the fatigue life time. This shows how impactful slight increases in the maximum load can considerably impact the fatigue life of the bridge deck.

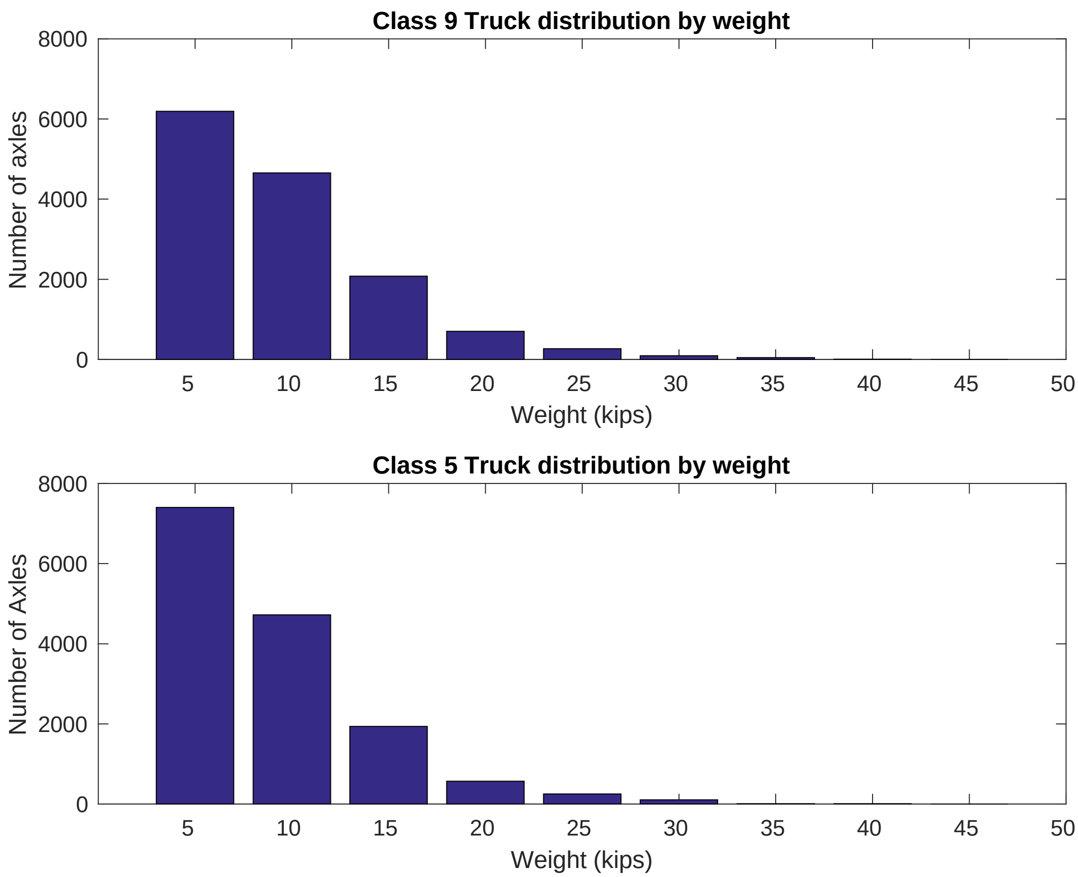

Figure 21: Class 9 and Class 5 axle load Histogram

To achieve an understanding of modeling crack propagation and stress concentration around the crack tip, the software tool Abacus is used for further investigation on the bridge member. In understanding the modeling techniques used in the Abacus software program, mesh and initial crack length must be initialized on the member. For simplicity, a two-dimension model is used for expressing information on the crack tip model. Figure 21 models the internal stresses on a plate with a two centimeter crack.

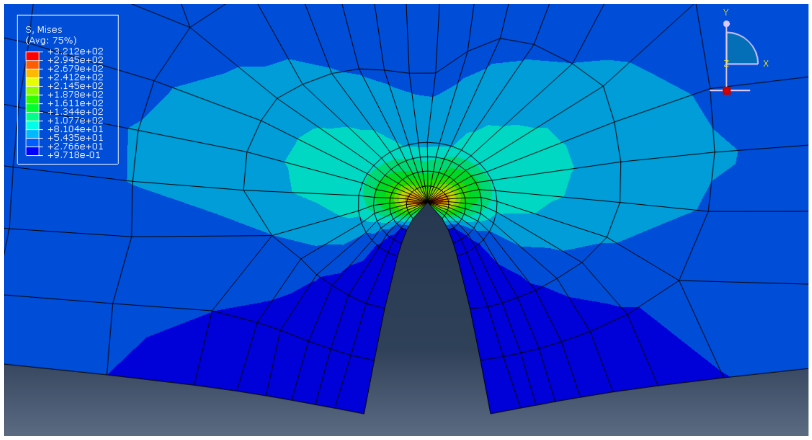

Figure 22: Stress Distribution at a Crack Tip

Figure 22 depicts the distribution of the stress in the crack tip. According to Figure 18, the stresses are concentrated at the crack tip. Therefore, it is important to reduce the maximum stress to avoid elongation of the crack tip.

Conclusion

Overall, the analysis of two truck scenarios demonstrates the influence of load models on fatigue life. Under the class 9 scenario we were able to transport more loads and have a higher fatigue life by adding more repetitions of axle loadings. The main reason for this impact is that there were more axle loads hitting the maximum stresses on the spectrum during the class 5 scenario on the bridge deck plate than the class 9 scenario.

The results of this study show that the steel deck is able to last approximately 51 more years under the class 9 truck load model than the class 5 truck load model. This means that the fatigue life span favors a model with lower axle loads with more repetition of the loads than higher axle loads with less repetition. Furthermore, the class 9 truck load case was able to carry 8.79 million kips extra than the class 5 truck case. This means that by lowering the maximum stress cycle, we can significantly increase the fatigue life of a bridge deck plate and also increase the amount of goods transported over the lifetime of the bridge deck.

Lastly, total fatigue life of the bridge deck plate under class 9 scenario is 125.99 years, while the total life span of the bridge deck plate under class 5 scenario is 74.69 years. Also, the total amount of cargo transported by the class 9 truck scenario is approximately 21.78 million kips and the total amount of cargo transported by the class 5 truck scenario is approximately 12.99 million kips.

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References

[1] Anderson, PhD T.L. Fracture Mechanics: Fundamentals and applications. Third Edition. Taylor and Francis Group. 2005

[2] Berger, Christina. Bruchmechanischer Festigkeitsnachweis für Maschinenbauteile:VDMA-Verl., 2001.

[3] Enginebasics. "Fact or Fiction? Tire Contact Patch Size Is Determined Mostly by Weight and Tire Pressure." Tire Contact Patch. N.p., n.d. Web. 31 Aug. 2016.

[4] H. Unterweger, P. Kugler, Remaining Fautigue Life of Steel Railway Bridges Improved models for considering realistic behaviour, Institut für Stahlbau, Technische Universität Graz, October 2016

[5] “Traffic Monitoring Guide.” U.S. Department of Transportation/Federal Highway Administration, 7 Nov. 2014, www.fhwa.dot.gov/policyinformation/tmguide/tmg_2013/vehicle-types.cfm.

[6] “Rating Conditions.” FHWA:NBI Data Dictionary, National Bridge Inventory, nationalbridges.com/nbiDesc.html.

[7] Triborough Bridge and Tunnel Authority. “Throgs Neck Structural Drawings.” TBTA Library.

Appendix A: Truck Data Analysis Code

```
% Truck Data Analysis
clc
clear
load AxleData

% Total weight of Trucks in the year
% Gross Vehicle weight: Column 4+([Axle Number]-1)

for axle=2:6
   TruckAxleGVW(axle-1)=sum(AxleData.(['Axle', num2str(axle)])(:,4+axle-1))./1000;
   A{axle-1}=[num2str(axle), ' Axles'];
   NumberofTrucks(axle-1) = size(AxleData.(['Axle', num2str(axle)])(:,4+axle-1),1);
end
GVW=sum( TruckAxleGVW);
N=GVW./TruckAxleGVW;TruckAxleGVWPercentage=TruckAxleGVW./GVW;
subplot(2,1,1)
bar(TruckAxleGVW)
set(gca, 'XTick', 1:5, 'XTickLabel', A);
title('Goods Transported by Truck Type')
xlabel('Number of Axles')
ylabel('Weight (kips)')
subplot(2,1,2)
bar(TruckAxleGVWPercentage)
set(gca, 'XTick', 1:5, 'XTickLabel', A);
title('Goods Transported by Truck Type')
ylabel('Weight by Percentage')
xlabel('Number of Axles')
figure
bar(TruckAxleGVW./NumberofTrucks)
set(gca, 'XTick', 1:5, 'XTickLabel', A);
title('Average Weight Transported by Truck Type')
ylabel('Average Weight (kips)')
xlabel('Number of Axles')
figure
% Distibution
GVW=AxleData.Axle5(:,8)./1000;
increment=10;
for i=increment:increment:(ceil(max(GVW)/increment)*increment)
   lables(i/increment) = i;
   distribution(i/increment)=length(find(GVW>i & GVW<(i+increment)));
end
subplot(2,1,1)
bar(distribution)
%lables = increment:increment:ceil(max(GVW)/increment)*increment;
set(gca, 'XTick', 1:length(lables), 'XTickLabel', lables);
title('Class 9 Truck distribution by weight')
ylabel('Number of trucks')
xlabel('Weight (kips)')
clear distribution i labels
GVW=AxleData.Axle2(:,5)./1000;
increment=5;
for i=increment:increment:(ceil(max(GVW)/increment)*increment)
   lables(i/increment) = i;
   distribution(i/increment)=length(find(GVW>i & GVW<(i+increment)));
```

```
end
subplot(2,1,2)
bar(distribution)
%lables = increment:increment:ceil(max(GVW)/increment)*increment;
set(gca, 'XTick', 1:length(lables), 'XTickLabel', lables);
title('Class 5 Truck distribution by weight')
ylabel('Number of trucks')
xlabel('Weight (kips)')
```

Appendix B: Fatigue Calculations Code

```
% K Calculation Anylysis
%EN-GJS-IOOO-5(S)
clear
clc
load AxleData
P1=[];
P2=[];
for N= 1: length(AxleData.Axle5)
   P1=[P1,AxleData.Axle5(N,9:13)];
end
for N= 1: length(AxleData.Axle2)
   P2=[P2,AxleData.Axle2(N,6:7)];
end
% Solve for K1
s=39.5*12; % inches
b= 1;% 25.4 mm Plate Depth
% Geometeric Shape function
f=@(r) 6*sqrt(2*tan(pi*r/2))/cos(pi*r/2)*(0.923+0.199*(1-sin(pi*r/2))^4);
d=6;
I = b^3*19.21/12+b*19.21*(d^2)/4;

%Kc= 50/1.09884;  %ksi*sqrt(in)
% constant based on experimental material property values unitless
C=2.51*10^-10; m=1.92;
Kth=6.2;
% ---------------------------------------------------------------------- %
%           Analysis with Class 9 (5 axles) Trucks
% ---------------------------------------------------------------------- %

k=0;
a0=.05;
a1=a0;
j=0;
i=0;

GVWapplied=0;
while j==0
   k=k+1;
for axle=1:length(P1)
       i=i+1;
       l=(2.2173*log(P1(axle)/1000)+7.1921)+7; % 3 inches extended on both
                                 % sides of the catual contact
                                 % length projected onto the
                                 % steel deck
       w=P1(axle)/(l); % lbs/in
       if l>s
          l=s;
       end
       M= (w*(l^2)/8)+ (w*l/8*(s-l)); %lbs*in Applied Moment
       %sig= 6*M/b^2/19.21/1000; % stress ksi
       sig= M*(b+d)/(2*I)/1000; % stress ksi
       r=a1/b;
       if i==1
          K(1) = sig*sqrt(pi*a1)*f(r)*1.09884;
```

```
        end
        K(i+1)= sig*sqrt(pi*a1)*f(r)*1.09884; % MPasqrt(m)

        if K(i+1)-K(i)>Kth %  there is fracture extention in the crack.
% After figuring out stress intensity factor, the next step is to otain the
% change in crack length from the next cycle. this will be a repetion of
% calculations because as the crack length increases so will the stress
% intensity factor.
            DeltaK=((K(i+1)-K(i))^m-Kth^m)/.0254;
            DeltaA = C*(DeltaK); % *(1-DeltaK(end-1)/DeltaK(end))/((1-max(K)/Kc)^3)
            a1=DeltaA+a1;
        end


        if a1(end)>1
            j=1;
            warning(['plate with class 9 loading broke at ',num2str(i), ' cycles'])
            break
        end
        stressSpectra1(i)=sig;
        GVWapplied=P1(axle)+GVWapplied;
end
    a1rec(k)=a1(end);
    GVWapplied1(k)=GVWapplied;
end

% ---------------------------------------------------------------------- %
%           Analysis with Class 5 (2 axles) and 8 Trucks (4 axles)
% ---------------------------------------------------------------------- %

k=0;
a2=a0; % initial Crack length
i=0;
GVWapplied=0;
j=0;
K=0;
while j==0
    k=k+1;
for axle=1:length(P2)
        i=i+1;
        l=(2.2173*log(P2(axle)/1000)+7.1921)+7; % 3 inches extended on both
                                    % sides of the catual contact
                                    % length projected onto the
                                    % steel deck
        w=P2(axle)/(l); % lbs/in
        if l>s
            l=s;
        end
        M= (w*(l^2)/8)+ (w*l/8*(s-l)); %lbs*in Applied Moment
        sig= M*(b+d)/(2*I)/1000; % stress ksi
        %sig= 6*M/b^2/19.21/1000; % stress ksi
        r=a2/b;
        if i==1
            K(1) = sig*sqrt(pi*a2)*f(r)*1.09884;
        end
        K(i+1)= sig*sqrt(pi*a2)*f(r)*1.09884; % MPasqrt(m)
```

```
        if K(i+1)-K(i)>Kth %  there is fracture extention in the crack.
% after figuring out stress intensity factor, the next step is to otain the
% change in crack length from the next cycle. this will be a repetion of
% calculations because as the crack length increases so will the stress
% intensity factor.
            DeltaK=((K(i+1)-K(i))^m-Kth^m)/.0254;
            DeltaA = C*(DeltaK); % *(1-DeltaK(end-1)/DeltaK(end))/((1-max(K)/Kc)^3)
            a2=DeltaA+a2;
        end
        if a2(end)>1
            j=1;
            warning(['plate with class 5 loading broke at ',num2str(i), ' cycles'])
            break
        end
        stressSpectra2(i)=sig;
        GVWapplied=P2(axle)+GVWapplied;
end
    a2rec(k) = a2;
    GVWapplied2(k)=GVWapplied;
end

% ---------------------------------------------------------------------- %
%                    Comparative Analysis
% ---------------------------------------------------------------------- %


Plots={a1rec,a2rec,GVWapplied1/1000, GVWapplied2/1000};%, Cnum1/(5*size(P,1)/1.8097),
Cnum1/(2*size(P2,1))/8.5957};
Ylabels={'Number of Cycles','Number of Cycles','Gross Vehicle Weight (N)', 'Gross Vehicle Weight (N)', 'Years for
failure','Years for failure'};
Titles={'# of Cycles for Failure from Class 9 Trucks','# of Cycles for Failure from Class 5 Trucks','','','',''};
for i=1:length(Plots)
    if mod(i,2)==0
        q = (1:length(a2rec))/8.5957*6;
    else
        q = (1:length(a1rec))/1.8097*6;
    end
subplot(2,2,i)
%figure
plot(q, Plots{i});
title(Titles{i})
xlabel('Years')
ylabel(Ylabels{i})
end
figure
bar([GVWapplied1(end),GVWapplied2(end)]*6/1000)
Labels={'Class 9', 'Class 5'};set(gca, 'XTick', 1:4, 'XTickLabel', Labels);
ylabel('Cargo Weight Passed before failure (kips)')
title('Total Weight Applied')
figure
bar([(length(a1rec))/1.8097, length(a2rec)/8.5957]*6)
set(gca, 'XTick', 1:4, 'XTickLabel', Labels);
ylabel('Years passed before failure')
title('Total Life Span')
figure
```

```
plot(1:length(stressSpectra1),sort(stressSpectra1,2,'descend'));hold on;
plot(1:length(stressSpectra2),sort(stressSpectra2,2,'descend'))
xlabel('Number of Loadings')
ylabel('Stress (ksi)')
title('Class 9 Trucks vs. Class 5 Trucks Stress Sectrum')
legend('Class 9', 'Class 5')
```