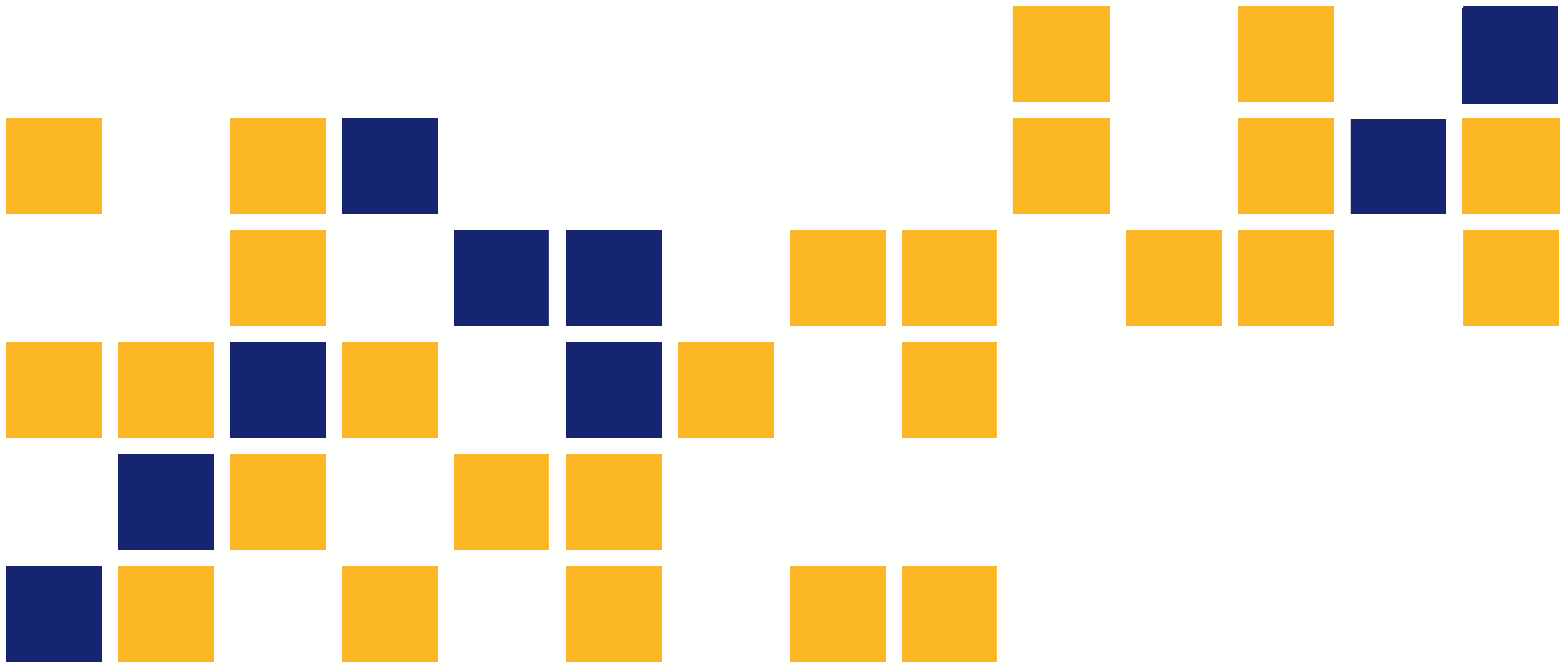


# Initial Analytical Investigation of Overhead Sign Trusses with Respect to Remaining Fatigue Life and Predictive Methods for Inspection

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<b>16 Abstract</b> <p>Most state highway agencies do not perform routine fatigue inspections on highway signs, luminaires, and traffic signals, thereby increasing the potential for unnoticed fatigue cracking. The Kansas Highway System utilizes over 450 sign trusses, most of which have been in service for 30–45 years. In addition to aging support structures, the structural designs of these signs and signals sometimes result in significant cyclical loading due to wind gusts. This study conducted fatigue evaluations using nominal axial member-specific stress ranges corresponding to a wind speed database for a 45-year period, as well as hundreds of structural analysis simulations. Potential fatigue failure was assessed for each member of the support structure by evaluating the ratio of consumed fatigue cycles to ultimate fatigue cycles using Miner’s rule to estimate finite life. If the ratio was close to zero after 45 years or any number of actual service years, the member was expected to have a practically infinite life. If the ratio was close to 1 after the service years, the member was expected to be at the end of its life. This information can help inspectors identify for critical spots that may have developed fatigue cracks that otherwise would be difficult to detect.</p> <p>Two approaches were hypothesized to account for fatigue life deterministically and probabilistically. Fatigue Life Simulator Software (FLSS) was developed to manage hundreds of simulations and determine the fatigue life of all members in a structure in specific areas of Kansas. FLSS is compatible and works simultaneously with STAAD.Pro software and Sign Truss Interface provided by KDOT to generate results. Users apply the results to study the behavior of overhead structures and identify critical spots that should be physically inspected and potentially replaced. Results in Kansas indicated a range of structural fatigue life varying by city. Modifications were made to the output files of Sign Truss Interface to incorporate American Association of State Highway and Transportation Officials (AASHTO) load cases 1 and 2 and simulate wind speed into wind pressure using the effect of the two load cases. The modification also automatically incorporated 45 years’ worth of wind speed data into the Sign Truss Interface to simulate and generate structural models to determine corresponding stresses to the wind effect.</p>					
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Final Report

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## **PREFACE**

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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## Abstract

Most state highway agencies do not perform routine fatigue inspections on highway signs, luminaires, and traffic signals, thereby increasing the potential for unnoticed fatigue cracking. The Kansas Highway System utilizes over 450 sign trusses, most of which have been in service for 30–45 years. In addition to aging support structures, the structural designs of these signs and signals sometimes result in significant cyclical loading due to wind gusts. This study conducted fatigue evaluations using nominal axial member-specific stress ranges corresponding to a wind speed database for a 45-year period, as well as hundreds of structural analysis simulations. Potential fatigue failure was assessed for each member of the support structure by evaluating the ratio of consumed fatigue cycles to ultimate fatigue cycles using Miner’s rule to estimate finite life. If the ratio was close to zero after 45 years or any number of actual service years, the member was expected to have a practically infinite life. If the ratio was close to 1 after the service years, the member was expected to be at the end of its life. This information can help inspectors identify for critical spots that may have developed fatigue cracks that otherwise would be difficult to detect.

Two approaches were hypothesized to account for fatigue life deterministically and probabilistically. Fatigue Life Simulator Software (FLSS) was developed to manage hundreds of simulations and determine the fatigue life of all members in a structure in specific areas of Kansas. FLSS is compatible and works simultaneously with STAAD.Pro software and Sign Truss Interface provided by KDOT to generate results. Users apply the results to study the behavior of overhead structures and identify critical spots that should be physically inspected and potentially replaced. Results in Kansas indicated a range of structural fatigue life varying by city. Modifications were made to the output files of Sign Truss Interface to incorporate American Association of State Highway and Transportation Officials (AASHTO) load cases 1 and 2 and simulate wind speed into wind pressure using the effect of the two load cases. The modification also automatically incorporated 45 years’ worth of wind speed data into the Sign Truss Interface to simulate and generate structural models to determine corresponding stresses to the wind effect.

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# Chapter 1: Introduction

## 1.1 Background

The Kansas Highway System currently utilizes over 450 sign trusses, most of which are 30–45 years old. Although all the sign trusses in Kansas contain welded aluminum connections that are potentially prone to fatigue, these structures have not undergone fatigue evaluation to determine remaining fatigue life. The structures are made of non-cantilevered configurations with many fatigue-prone details, and these details must be examined to evaluate their performance over time. The safety and intended performance of non-cantilevered highway support structures of signs and traffic signals must be maintained to adequate traffic flow and safety. However, system failures due to fatigue failure within the structures have been determined including mast-arm-to-column connections, column-to-base-plate connection, and anchor bolts, as shown in Figures 1.1 and 1.2. Even though these examples do not relate directly to non-cantilevered structures, they indicate that all types of support structures must be examined. Unpredictable fatigue failures of many structures throughout the United States require the investigation of overhead structure fatigue behavior.

Figures 1.1 and 1.2 show fatigue failure in traffic structures in different states throughout the nation. One study showed that in Missouri, a dozen traffic signal mast arms fractured at the arm-post weld connections, most of which had lost function after 1–2 years of service, while other traffic structures stayed in service for more than 20 years (Chen, Wu, Yu, Dharani, & Barker, 2001). A visual inspection of 840 signal structures in Wyoming revealed that more than one-third of the structures had fatigue cracks ranging in length from 0.25–20.0 inches at the pole-to-arm connection (Hamilton, Riggs, & Puckett, 2000). Structures in Texas also experienced several recent fatigue failures, including one failure each in the cities of Pflugerville and Lubbock. Fatigue failure results from overstressing, poor welding quality, and low fatigue strength, as demonstrated in Missouri, Wyoming, and Texas (Florea, Manuel, Frank, & Wood, 2007).

Modeling, analysis, and structural assessment often reveal nominal stress range levels needed to estimate the remaining life of structural connections. In addition, with increased guidance, inspectors can identify fatigue cracks that otherwise would have been difficult to detect. Therefore, this study was initiated to fully evaluate the existence of infinite fatigue life and

potentially estimate the remaining life for each aluminum connection as required by AASHTO LRFD procedure.



**Figure 1.1: Falling Cantilevered Highway Sign Structure**

Source: Florea et al. (2007). The photo is a courtesy of Professors Dr. Lance Manuel and Dr. Karl Frank at University of Texas at Austin.



**Figure 1.2: Fatigue Failure at Mast Arm Connection of Traffic Signal**

Source: Florea et al. (2007). The photo is a courtesy of Professors Dr. Lance Manuel and Dr. Karl Frank at University of Texas at Austin.

Research has shown that excessive vibration of non-cantilevered support structures of signs and signals is caused by natural wind gusts. This leads to significant amplitude displacement and

associated stress ranges. Dexter and Ricker (2002) suggested increasing the span of structure configurations to improve driver safety by moving the upright farther from the roadway, especially on multi-lane highways. Increasing structures, however, make them more susceptible to wind vibrations. This susceptibility causes the structures to have low resonant frequencies, 1 Hz, so wind vibration fluctuates within that frequency range (Dexter & Ricker, 2002). Consequently, these support structures tend to be more susceptible to large amplitude vibration due to various wind loading phenomena. As the flexibility of these support structures increases during years of service, the number of problems associated with vibration and fatigue also increases. Additionally, attachments such as signs and signals negatively impact support structures by generating vibration susceptibility. As a result, high stress ranges associated with vibration eventually cause fatigue cracking of support details such as mast-arm-to-column connection details, column base plate, and anchor bolts.

## **1.2 Objectives**

Non-cantilevered highway support structures of signs and traffic signals are essential within a traffic management system, so their safe and intended performance is necessary to maintain adequate traffic flow and safety. However, there are documented failures of these systems due to reaching fatigue limit state in many spots within the structures. Therefore, a study was initiated to fully evaluate the remaining life span of overhead welded aluminum support structures. This study is conducted to investigate the behavior of the structures and develop a software that is capable of estimating the fatigue life based on daily wind speed fluctuation. This analytical study had three primary objectives, which are addressed below:

- The first objective was to evaluate and determine the finite remaining fatigue life of non-cantilevered aluminum structural supports for highway signs, luminaires, and traffic signals in Kansas.
- The second objective was to guide inspectors as they identify critical spots that may have developed fatigue cracks that otherwise would have been hard to detect.

- The third objective of this study was to develop programmatically an analytical model, “Fatigue Life Simulator Software” (FLSS), to implement analysis and determine the fatigue life of structural members. The FLSS must be compatible with STAAD.Pro Software and Sign Truss Interface to work simultaneously to present results.

### **1.3 Scope**

This report contains seven chapters as well as two appendices, which are available separately upon request. Chapter 1 includes the introduction, which consists of background, objective, and scope of this research. Chapter 2 contains the literature review, and sections on Fatigue Life, S-N Curve, Deterministic Model of Fatigue Analysis, Probabilistic Model of Fatigue Analysis, and Sign Truss Interface. Chapter 3 focuses entirely on Formulation by Deterministic Approach, which includes sections on the State of Kansas Cities, Regions, and Seasons, Wind Speed Raw and Extended Data, Wind Fluctuation Model, Using Sign Truss and STAAD.Pro to Generate Stresses, Selected Stress Ranges for Fatigue Life, and Procedure for Estimating the Remaining Fatigue Life. Chapter 4 includes results and discussions. Chapter 5 discusses the Fatigue Life Simulator Software (FLSS) functionality and procedure. Chapter 6 explains Probabilistic Verification of the Deterministic Approach. Chapter 7 covers the conclusions and recommendations.



## Chapter 2: Literature Review

This chapter highlights research studies in the literature that pertain to this investigation. The papers are presented chronologically according to their publishing.

### 2.1 Fatigue Life

Pulipaka, Sarkar, and McDonald (1998) proposed that cantilevered sign and signal support structures possess aerodynamic characteristics that increase structural susceptibility to natural wind speeds. The authors conducted a series of experiments in two tanks and a wind tunnel that revealed that certain configurations of traffic signal structures satisfy the Glauert-Den Hartog criterion (Den Hartog, 1932) for vibration. The research also indicated that large amplitude vibrations occur when wind blows from behind signal lights with attached back plates. However, use of a wing mounted above the signal lights was shown to reduce the build-up of large vibration amplitude by increasing aerodynamic damping. Although a flat plate wing with rounded edges may work, a simple flat plate wing mounted directly on a single light head was a sufficient, simple solution for large amplitude vibration on signal traffic light structures.

Several changeable message sign structures on Interstate 15 in San Bernardino County, California, developed cracks at their post-base-plate connections due to wind-induced high-cycle fatigue (Gilani & Whittaker, 2000). This failure prompted the inspection of all changeable message sign structures to evaluate the extent of initiated cracking. The field investigation revealed that numerous changeable message sign structures were exposed to constant high winds, which caused fatigue cracks at the post-base plate connections. Based on Gilani and Whittaker, the field data show that the welded components were subjected to stress ranges that exceeded permissible values recommended by AASHTO specifications. This research concluded that galloping instability was not advised by AASHTO for fatigue cycle-life evaluation of changeable message sign structures. Conduit-hole geometry (rectangular, rectangular with radius-cut corner, or circular) had been recognized as minimally affecting the maximum value of lateral stress of a conduit's hole. Maximum stresses in the lateral post-to-conduit hole decreased drastically when wind gussets were used at the baseplate's post. Gilani and Whittaker used finite element analysis to determine that the conduit hole was the most critical cross section area due to its unreinforced condition.

Dexter and Ricker (2002) added information about fatigue wind loads for cantilevered sign structures to NCHRP Report 469 (*Fatigue-Resistant Design of Cantilevered Signal, Sign, and Light Supports*). The authors indicated that vibrational forces tend to increase as wind velocities increase. Therefore, the constant static pressure of 1,000 pa was based on engineering judgment to provide appropriate wind speed induced forces. While other researchers had suggested 1,000 pa to be too conservative, Gilani and Whittaker (2000) indicated that appropriate static loads may be twice that value in some conditions. They also suggested that three-dimensional three and four chord trusses are not susceptible to significant vortex shedding and that these structures should be designed based on natural winds only. In addition, Gilani and Whittaker indicated that fatigue cracks had been observed in several states in structure locations such as weld between base-plate and stiffener, post-to-base plate, tube-to-tube weld, mast arm connection, anchor rods, and conduit opening. Dexter and Ricker (2002) proposed ground rules pertaining to the inspection and maintenance of anchor bolts and overhead support structures. Visual inspection, a dye-penetrant technique, and use of a hammer to strike the top of bolts and the side of the top nut were recommended for inspecting anchor rods, as well as ultrasonic inspection of anchor rods if a previous inspection method revealed a problem at the anchor rods. Moreover, the authors (Gilani and Whittaker) suggested a regular maintenance procedure that includes verification of no rotating, tilting, or sagging of the sign, no broken or missing pieces, no obvious electrical issues, secure sign and signal attachments, good condition of foundation and anchor rods, integrity of the coating system, no fatigue cracks in structure or anchor bolts, and proper tightness of all bolted joints. Regarding the frequency of the inspection, the authors proposed that structures with aluminum components should be inspected on a 2-year cycle. Cantilever sign structures should be inspected every 4 years. Bridge type sign cantilevered support structures should be inspected at intervals greater than 6 years.

Repetto and Solari (2001) found that total damage due to fatigue phenomenon caused by variable amplitude loads was slightly difficult to predict, so they recommended a mathematical model to derive a histogram of stress cycles, accumulated damage, and fatigue life of slender vertical structures in the along wind vibration direction. In the published paper, model results from the vertical structures were treated as narrow band process, which drastically simplified the

representation of wind velocity. The method was further divided into the broad band process of mean wind speed plus variations. Natural wind speed was assumed to cause fatigue damage. The authors concluded by emphasizing a comparison between analytical solution and numerical simulations how burdensome the time domain approach is. The paper also generalized stress distributions due to crosswind vibrations induced by wind gust caused by lateral turbulence. The authors added, the mean total damage and potential fatigue life to their probability density functions is recommended. The mentioned functions should be taken correctly into consideration model error and parameter uncertainties which includes the distribution of mean wind velocity and spectral properties of wind turbulence.

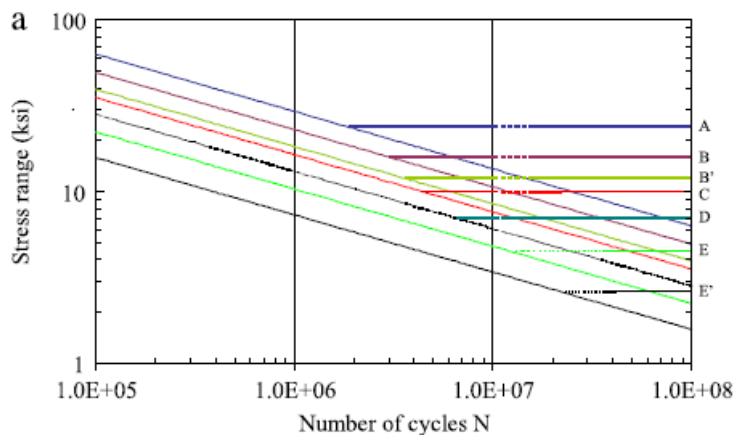
## **2.2 S-N Curve**

Holmes (2002) proposed closed form expression for high and low ends of fatigue life for structures under constant wind loading. Narrow band resonant response and wind band background response were considered, and natural wind was considered to induce fatigue damage. Variation of the amplitude of natural wind speed creates fluctuating stresses in the sign and signal support structures with contributions from resonant and sub-resonant connection details. The magnitude of each portion depends on natural amplitudes and damping of the structures. The purpose of this study was to determine whether fatigue under wind cyclic loading was causing fatigue damage on structures. The author proposed that each cycle of stress response inflicts an increment of damage which depends on the amplitude of the stress. Each subsequent cycle then generates additional damage that accumulates in proportion to the number of cycles until failure happens. The author represented S-N curve as the expressed form result of the constant amplitude fatigue tests, where S is the stresses and N is the number of cycles until the structure fails. Study conclusions determined closed form expressions are advantageous when estimating upper and lower boundaries of a structure's fatigue life. Assumption had to be made by the author to reach to his conclusion; nevertheless, numerical simulations were utilized for wind band vibration. The author showed that, instead of extensive numerical calculations, closed form expressions can be used to find fatigue under wind loading.

Li, Whalen, and Bowman (2005) studied fatigue strength and evaluation of highway structures to evaluate cracking due to fatigue damage in critical spots on sign structure. The analytical research focused on double-mast-arm cantilever sign structures, box-truss sign structures, and nanotube sign structures. Finite element models of the sign structures were developed based on selected structures. According to Li et al., fatigue life curves in AASHTO specifications are S-N curves. These S-N curves were plotted with stress ranges on y-axis and number to failure on x-axis for seven detail categories; both axes were logarithmic representations. Over a portion of the range, each detail had a sloping straight line with a slope constant, specific to the detail category. The fatigue lifeline was horizontal, and fatigue strength curves were based on a large database of constant amplitude loading test results of specimens with specific structural details. Variable amplitude fatigue limit (VAFL), which is one-half the constant amplitude fatigue limit (CAFL) used for bridges, was used to continue the sloping straight line in the S-N curve down to half of the CAFL, and then extends horizontally. This method assumes that all stress cycles below VAFL induce no fatigue damage, and all stress cycles above VAFL cause fatigue damage, while also accounting for the impact of variable amplitude on fatigue life. This method was not as conservative as the straight S-N curve method, which more reasonably approximated actual behavior, but a linear sloped S-N curve proved that the fatigue strength curve continues below the CAFL with the same constant slope. It means there is no fatigue limit existing and all stress cycles contribute to fatigue damage. It should be noted and based on Li et al. that the linear sloped S-N curve produces more conservative fatigue lives than both the CAFL and VAFL methods.

Kacin, Rizzo, and Tajari (2010) addressed the highway support structures such as variable message signs (VMSs), which are prone to fatigue due to natural wind loading. The VMSs are used to control traffic and guide motorists through exhibiting messages, but over time, the structure's members may become susceptible to fatigue due to constant cyclic loading. In this paper, an algorithm to determine the fatigue life of an overhead four-chord truss sign structure was presented. The algorithm included time varying natural wind loading and a finite element model. The stress history of selected critical elements was extracted from the model's solution, and the fatigue life of members was predicted using linear damage accumulation and stress ranges. S-N

curve methods were used to determine the number of cycles to fatigue that correspond to stresses. According to Kacin et al., each S-N curve point has a discontinuity point after which the value of the stress range is independent of the number of cycles, as shown in Figure 2.1. Furthermore, fatigue provisions utilized an infinite life design basis, requiring that the maximum stress range within the load spectra be less than the corresponding CAFL for the specific connection detail. The discontinuity points in Figure 2.1 identify the CAFL, showing that the detail theoretically provided infinite life. AASHTO specifications contain seven design categories: A, B, B', C, D, E, and E'. Examples for details, anchor bolts (category D), post to base plate socket weld connection (category E'), mast arm to flange plate socket connection (category E'), and hand hole opening (category E).



**Figure 2.1: S-N Curve and its Categories from A to E'**

Source: Kacin et al. (2010). Courtesy of Dr. Piervincenzo Rizzo, Associate Professor at Pittsburgh University July 2018.

Kacin et al. (2010) sought to determine critical spots of VMSs by investigating a four-chord box truss in Pennsylvania. The structure was modeled using the finite element program ANSYS, and dynamic structural analysis was conducted to evaluate the effect of natural wind on the fatigue life of five critical elements of the truss.

### 2.3 Deterministic Models of Fatigue Analysis

Fatemi and Yang (1998) studied fatigue damage based on cumulative damage due to loading cycling. Their research found that cumulative damage analysis must be conducted to

predict the life span of a structure, especially structures subjected to field load histories. According to this case study, however, no comprehensive report has reviewed and summarized the analysis of fatigue cumulative damage, even considering early theories on cumulative fatigue damage models. Therefore, this study reviewed and illustrated fatigue cumulative damage behavior, which increases with applied cycles leading to fracture. Cumulative fatigue damage is an old, but not yet resolved, problem. In 1924, Arvid Palmgren suggested the concept, which is now known as the “Linear rule.” Later in 1945, Miner’s rule came to existence when M. A. Miner introduced the expression mathematically as  $D = \sum (n_i/N_i)$ , where D denotes the damage, and  $n_i$  and  $N_i$  are the applied cycles and total cycles to failure under  $i$ th cyclic loading respectively. Since then, more attention has been paid to cumulative fatigue damage. The case study had discussed also the crack growth concept. It indicated that since the crack growth concept is directly related to damage accumulation, modern technology has increasingly progressed to enable measurements of very small cracks in an order of minutes. The research concluded that Palmgren and Miner Rule approaches are dominantly used in design.

Maddox (2003) studied and reviewed methods and corresponding codes and standards for fatigue assessment of welded aluminum alloy structures. The focus of the original design and estimation of residual life of existing structures included fatigue evaluation of welded aluminum structures. Data used in the case study were gathered from literature and information available for design assessments or guidance specifications as related to relevant fatigue data. Maddox identified a growing interest in the use of aluminum structures for applications such as automotive, railway vehicles, bridges, off-shore structure topsides, and high-speed ships. In all cases, welding was the primary joining method and fatigue was a major design criterion. Welded joints and members often exhibit poor fatigue properties due to accumulated damage, however, so Maddox’s research sought a clear design guideline to avoid fatigue failure in welded aluminum structures. Research results also indicated increasing interest in methods to assess the remaining fatigue lives of existing structures. S-N curve as nominal applied cyclic stress S and corresponding number of cycles N were recommended to gather fatigue resistance data. The research also investigated the remaining life of existing structures already in service. Conclusions revealed that the S-N curve

approach is the most developed and standardized approach for fatigue resistance. The literature provided minimal information regarding remaining life assessment procedures.

Kocańda and Torzewski (2009) studied aluminum structures to predict fatigue crack growth under variable amplitude loading. The case study utilized a deterministic approach to try to predict the fatigue crack growth rate in a component subjected to variable amplitude loading with over/under load cycles. Research data was developed based on experimental data obtained for aluminum alloy sheet CCT specimens under LHL type block program loading with multiple over/under load cycles. Moreover, the effect of block program loading was traced on the crack growth rate using micro-fractographic analysis of fatigue fracture via a transmission electron microscope. Experimental specimens in this study showed that crack growth rate can be determined based on fatigue striation spacing on the fracture surface. Micro-fractographic analysis proved that a crack propagates for a time that approximately corresponds to 4.2% of the spectrum operation. Additionally, crack growth behavior resulting from the plastic zone was developed by the highest stress level due to the cyclic loading affect.

## **2.4 Sign Truss Interface**

Sign Truss Interface is a program used by KDOT to simulate wind pressure using information for a specific structure model including: number and spacing of panels for vertical elements (columns) and horizontal span truss elements, off-set distance of the horizontal span truss from columns on both sides of the structure, velocity value, and wall thickness of the main and secondary elements of the structure. For KDOT to generate a specific structure model using Sign Truss Interface, users must input previously mentioned information and press “Run” to generate a model through STAAD.Pro Software. When KDOT first began using Sign Truss Interface, it was unable to calculate fatigue life based on load combination 17 (i.e., wind speed as it blows perpendicular to structural members and the highway signs) and load combination 19 (wind speed as it blows perpendicular and transverse to structural members and the highway signs). Therefore, a modification was made to the output files of the interface to allow calculation of fatigue lives based on effects of the two load combinations. These modifications were done using FLSS, which took the output files of the interface and added either one of the load combinations based on the

users' desires, removed all unwanted loads, and then calculated fatigue lives. Three structure models were tested using Sign Truss Interface. These models were created by inputting different dimensions in Sign Truss Interface to create multiple models for testing. Figures 3.7, 3.9, and 3.11 show Sign Truss Interface for three representative models with their correlated data for each model.

## **2.5 Probabilistic Verification of the Deterministic Model**

This section describes the probabilistic approach, an approach distinct from the deterministic approach to calculate wind speed fluctuation during the day and verify the accuracy and validity of the  $\frac{1}{4}$ -day recurring model. Although the National Weather Service compiled wind speeds over 45 years (Iowa Environmental Mesonet, n.d.), this data does not identify wind speed fluctuations during the day. To determine the fluctuation during the day for high, medium, and low speeds, the authors proposed an approach called the  $\frac{1}{4}$ -day recurring model. This model determines the behavior of the wind speed during the day, so the model presumes the wind is at high speed for  $\frac{1}{4}$ -day, medium speed for  $\frac{1}{2}$ -day, and low speed for  $\frac{1}{4}$ -day. Based on this assumption, the wind speed fluctuation during the day was calculated. Thus, a probabilistic approach was created (as discussed further in Chapter 6) to study and validate the presumption of the  $\frac{1}{4}$ -day recurring model. The probabilistic approach took the 45 years' worth of wind speed into the calculation by splitting the data into seasons, instead of taking the data as a whole—just like in the deterministic approach. The probabilistic approach determined the speed repetitions of the speed values just for a specific season, but for 45-year period. The probabilistic approach also determined speed repetitions for speed values with non-zero value. In other words, any speed value that was zero or had zero speed repetitions, was eliminated from the calculation. Only speeds with actual values were incorporated into the calculations. Moreover, Chi-Square Statistic was utilized in this analysis to measure the goodness of fit and calculate the significant difference between deterministic approach data (expected date) and the probabilistic approach's data (observed data). If the difference was significant, then the model was inaccurate; if the difference was minimal, then the model was accurate and reliable.



## Chapter 3: Formulation by Deterministic Approach

### 3.1 Wind Speed Raw and Extended Data

Variability in wind speed is caused by natural change in wind flow direction and velocity. Changes in wind speed and direction cause fluctuating pressures on various components and connections of traffic sign and signal support structures, potentially leading to static deformation of the structures. If static deformation occurs due to wind speed loading, stresses are expected to be widely distributed, and the cumulative effects of these vibrations over the life of structures may result in fatigue cracking. The state of Kansas is divided into eight regions as represented by eight cities to accurately capture local variations in wind speed and direction (Figure 3.1). Utilizing the concept of wind energy, this research considered kinetic energy to convert wind speed into pressure to calculate wind-induced effects on structures and structures' attachments.

Structures and their attachments were subjected to wind speed in various directions with magnitudes indicated in wind speed data from the National Weather Service (Iowa Environmental Mesonet, n.d.). As shown in Table 3.1, high speed and medium speed values were collected, as measured in miles per hour (mph). Low speed values were estimated to complete a full wind cycle. The full variation of wind speed simulated wind fluctuation throughout the day. A full cyclic loading effect inflicts increments of damage depending on the amplitude of stress as a function of wind speed.

**Table 3.1: Estimated Speed Data for High, Medium, and Low Wind**

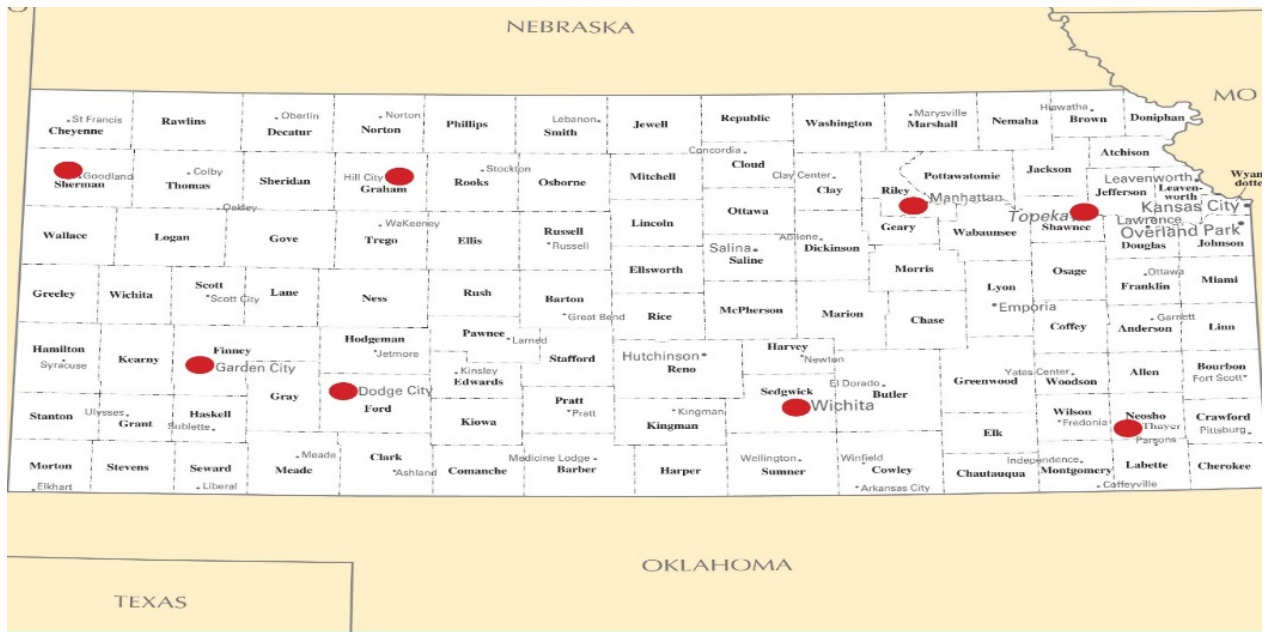
Years: 1975, 1976, 1977, 1978, 1979			
# of Days	High-Speed (mph)	Medium-Speed (mph)	Low-Speed (mph)
1	29	14	0
2	32	25	18
3	16	13	10
4	21	13	5
5	32	20	8
6	17	12	7
7	26	14	2
8	23	14	5
9	30	17	4
10	30	21	12
11	22	15	8
12	21	14	7
13	21	14	7
14	17	12	7
15	29	16	3
16	25	12	0
17	16	10	4
18	46	16	0
19	25	17	9
20	17	13	9
21	28	18	8
22	23	13	3
23	14	10	6
24	33	15	0
25	18	11	4
26	21	12	3
27	29	19	9
28	30	17	4
29	21	12	3
30	26	17	8
31	15	9	3

### 3.1.1 The State of Kansas Regions, Cities, and Seasons

Since the State of Kansas is considered “the alley of high wind speed and tornadoes,” the data generated for the entire state was expected to vary drastically in intensity and variation. Therefore, this study divides Kansas into eight regions: north, west, south, east, northeast, northwest, southeast, and southwest, as shown in Table 3.2. One city was selected to represent each region because insufficient data was available for other cities in Kansas. The criteria for a complete data set included wind speed data for the 45-year period with 9 representative years (i.e., a year’s worth of data was repeated to populate 5 consecutive years). Therefore, one city was selected per region because that city had a complete data set. For example, wind speed data from Manhattan represents the northeast region, Hill City represents the north region, Wichita represents the south region, Garden City is chosen for the west region, Dodge City represents the southwest region, Topeka represents the east region, Chanute represents the southeast region, and Goodland represents the northwest region, as indicated in Figure 3.1.

**Table 3.2: Representations of Kansas Regions Using Eight Cities**

<b>City</b>	<b>Region</b>
Manhattan	Northeast
Hill City	North
Wichita	South
Garden City	West
Dodge City	Southwest
Topeka	East
Chanute	Southeast
Goodland	Northwest



**Figure 3.1: Kansas Regions and Selected Cities**

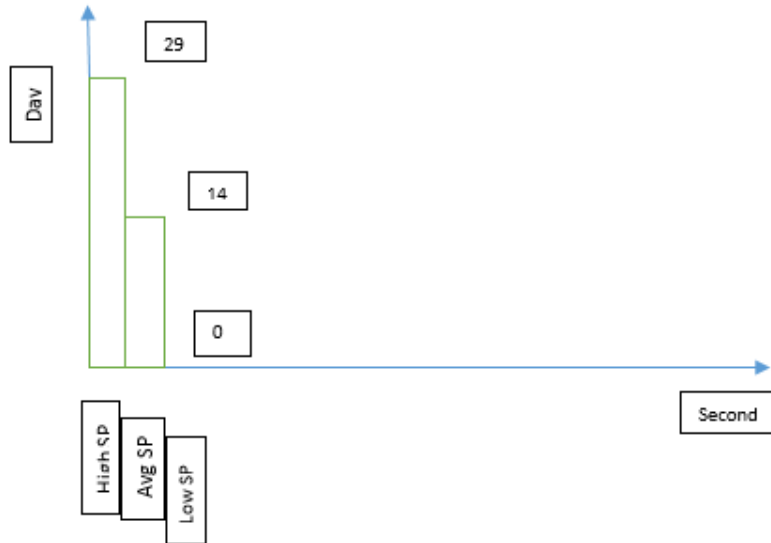
The 45-years' worth of data was subdivided into nine groups, with each group consisting of 5 years of repeated data. For example, 1975–1979 was the first group of the wind speed data, and the first year of data 1975 was repeated for the years 1976, 1977, 1978, and 1979. The data was repeated multiple times because the National Weather Service did not provide wind speed data for every year. The same process was applied for the rest of the groups within the 45-year period. Since each year consists of four seasons, one month was selected from each season and its data was populated for the entire season. For instance, the month of January represents the winter season, so data from January was populated to represent December and February. Furthermore, the month of April represents the spring season, so data from April was populated to represent March and May. In some years, May's data was utilized instead of April's data due to insufficient or incomplete data. Therefore, May's data was populated for April and March. July's data represents the summer season, so its data was populated for June and August. September represents the fall season, so its data was populated for October and November.

### 3.2 Wind Fluctuation Model

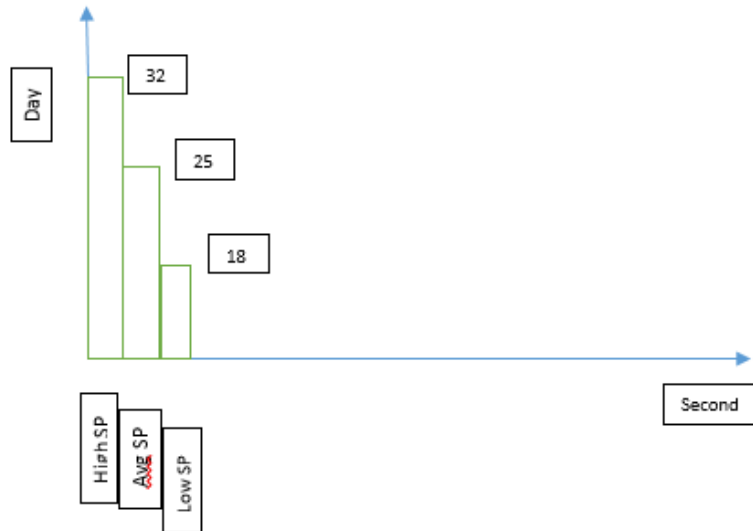
As mentioned, the National Weather Service data did not include low speed data, so low wind speed values had to be estimated to complete a full range of values. Figure 3.2 presents high,

medium, and estimated low wind speed values for the first day of the year (January 1, 1975). Figure 3.3 shows the wind speed values at high, medium, and estimated low wind speed value for the second day of the year (January 2, 1975). The values in the two figures were taken from Table 3.1.

The low wind speed values in Figures 3.2 and 3.3 were derived by maintaining equal distances between the high speed and the medium speed and between the medium and low speeds. In other words, the medium speed was subtracted from the high speed, and that number was subtracted from the medium speed to determine the low speed. For example, if the high wind-speed value is 29 mph and medium wind speed is 14 mph, then the low speed formula is  $14 - (29 - 14) = -1$ . If calculation results render the low speed to be negative, the low speed is assumed to be zero, as shown in Figure 3.2. In Figure 3.3, the high wind speed value is 32 mph and medium wind speed value is 25 mph. Figure 3.3 shows the same estimation, so if  $25 - (32 - 25) = 18 > 0$ , then 18 mph is the low wind speed value. This process was applied to all daily speed values to calculate low wind speed levels.



**Figure 3.2: Estimation of Low Wind Speed Value for January 1, 1975**



**Figure 3.3: Estimation of Low Wind Speed Value for January 2, 1975**

Figure 3.4 illustrates the  $\frac{1}{4}$ -day recurring model, which is composed of a full sinusoidal cycle of high wind speed, medium wind speed, and low wind speed fluctuations. The  $\frac{1}{4}$ -day model was created to simulate the total number of seconds for each wind speed cycle during one day. The model assumes the high wind speed to dominate during one quarter of the day. Additionally, the medium wind speed cycles are assumed to govern for half of the day, giving the low wind speed cycle control over the remaining of quarter of the day. This reflects the dominance of the medium wind speed during the day. This is called the deterministic model since the wind cycle fluctuations are pre-determined. Consequently, the wind speed distribution throughout the day is specified as follows:

$$1 \text{ hour} = 3,600 \text{ seconds}$$

$$1 \text{ day} = 24 \text{ hours}$$

$$1 \text{ day} = 3,600 \times 24 = 86,400 \text{ seconds}$$

$$\text{High Speed} = 86,400 \times \frac{1}{4} = 21,600 \text{ seconds/day}$$

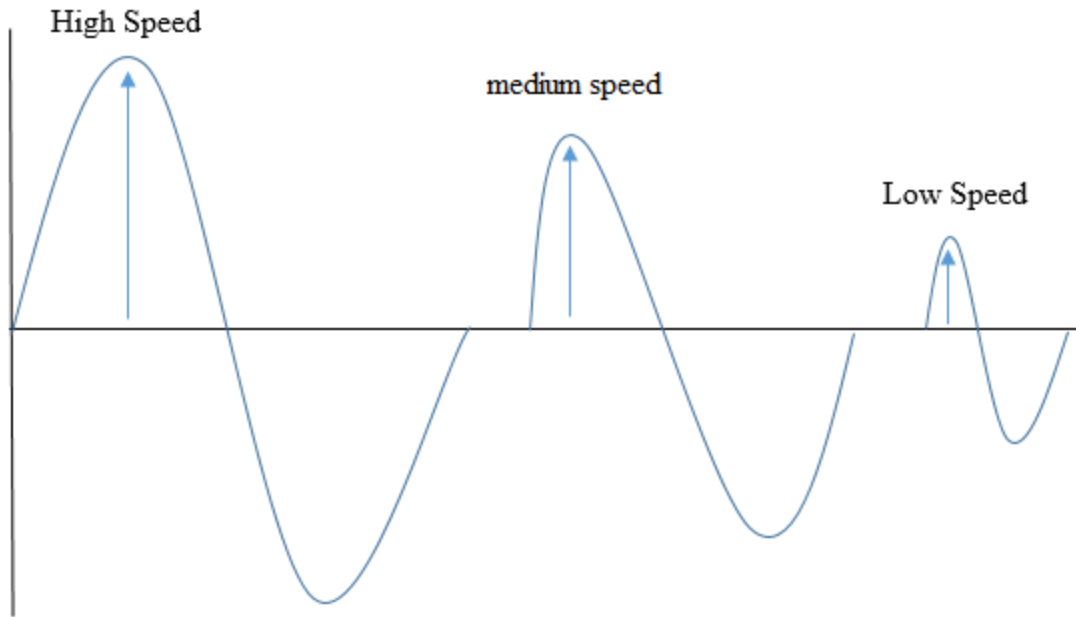
$$\text{Medium Speed} = 86,400 \times \frac{2}{4} = 43,200 \text{ seconds/day}$$

$$\text{Low Speed} = 86,400 \times \frac{1}{4} = 21,600 \text{ seconds/day}$$

The wind speed distribution pattern depicted in Figure 3.4 facilitates the prediction of the wind speed behavior during the day. The distribution pattern in Figure 3.4 is referred to as the  $\frac{1}{4}$ -day recurring model. It cannot be assumed that the wind speed was high for the entire day, or

medium or low, so the  $\frac{1}{4}$ -day recurring model helps to simulate the fluctuation of the wind speed during the day according to its intensity. Therefore, it was assumed that the fluctuation behavior of the wind speed is presented by a sinusoidal wind cycle pattern that divides a certain day into  $\frac{1}{4}$  of the day as high speed,  $\frac{1}{2}$  of the day as medium speed, and  $\frac{1}{4}$  of the day as low speed. As a result, the percentage weight of high wind speed during the day is 21,600 seconds. The 21,600 seconds of the percentage weight of the high speed during the day is resulted from multiplying  $\frac{1}{4}$  by the total number of seconds per day, 86,400 seconds. This means that the high wind speed gusted 21,600 seconds during a certain day. The medium wind speed lasted 43,200 seconds during a certain day. The 43,200 seconds is the percentage weight of the medium speed during the day and resulted from multiplying  $\frac{1}{2}$  by 86,400 seconds. The low wind speed dominated 21,600 seconds during a certain day. The 21,600 seconds of the percentage weight of the high speed during the day results from multiplying  $\frac{1}{4}$  by the total number of seconds per day, 86,400 seconds. These percentage weights of each wind speed type help determine speed repetitions at every speed value, as shown in Table 3.3. Furthermore, finding the percentage weight of each speed type allows accurate prediction of repeated speed throughout the day and up to 45 years.

The repeated speeds, however, help researchers determine fatigue life ratios at each stress range level. For instance, instead of the long, tedious process of individually dividing each speed value by its corresponding N-cycles for 45 years' worth of data, wind speed distribution can be utilized to count speed repetition for each speed value (Figure 3.4). Then, the summation of total speed repetitions within a certain stress range can be divided by an ultimate N-cycle value at that stress range level from the S-N curve to find the accumulated damage or ratio of fatigue life consumed.



**Figure 3.4: The ¼-Day Recurring Model having Three Dominant 1 Hz Wind Speed Cycles**

The collected 45 years' worth of data was generated for the eight cities indicated in Table 3.2 to establish a database for calculating speed repetitions. Table 3.3 below represents how the speed repetitions were calculated for Manhattan as a general example. The table is divided into four groups: the first group includes high wind speed data, second group contains medium wind speed data, the third group shows low wind speed data, and the fourth group combines speed repetitions per speed value. Table 3.3 presents the four groups of data for 10 speed values (0–10 mph) for illustration purposes; the complete data table is presented in Appendix A, which is available separately upon request. The first column of the first group, “speed,” contains speed values which range between 0 and 10 mph in Table 3.3. The second column, “repeated values,” contains the number of daily repetitions of each speed throughout 45 years. For example, the speed value 4 mph in the speed column was repeated 30 times as high speed during the 45-year period. The third column which is “High\*21600” is the column where the fluctuation weight of the high speed during the 45 years calculated by multiplying the daily repetition of speed 4 which is 30 times by 21,600 cycles/day, resulting in the value of 648,000 cycles total in 45 years. The same method of calculation was used for the other two groups (i.e., medium and low wind speeds). Afterwards, the speed repetitions of each speed type high, medium, and low were added to one full speed repetition for each speed value. For example, at speed value 4 mph, repetition of the



three speed types (high speed which is 648,000 cycles, medium speed which is 69,336,000 cycles, and low speed which is 17,409,600 cycles) all added up to be 87,393,600 cycles for the entire 45-year period.

Consequently, all the speed repetitions at every speed value were determined following the same procedure for the 45-year period. It was useful to check if the total number of repetitions for all speeds was equal to the total number of seconds in 45 years. This number was found to check nicely to the value of 1,419,897,600 seconds. The total number of seconds in 45 years was found from the following calculation: 86,400 seconds per day  $\times$  (5  $\times$  365 + 1) days per 5 years  $\times$  9 groups of 5 years per 45 years = 1,419,897,600 seconds.

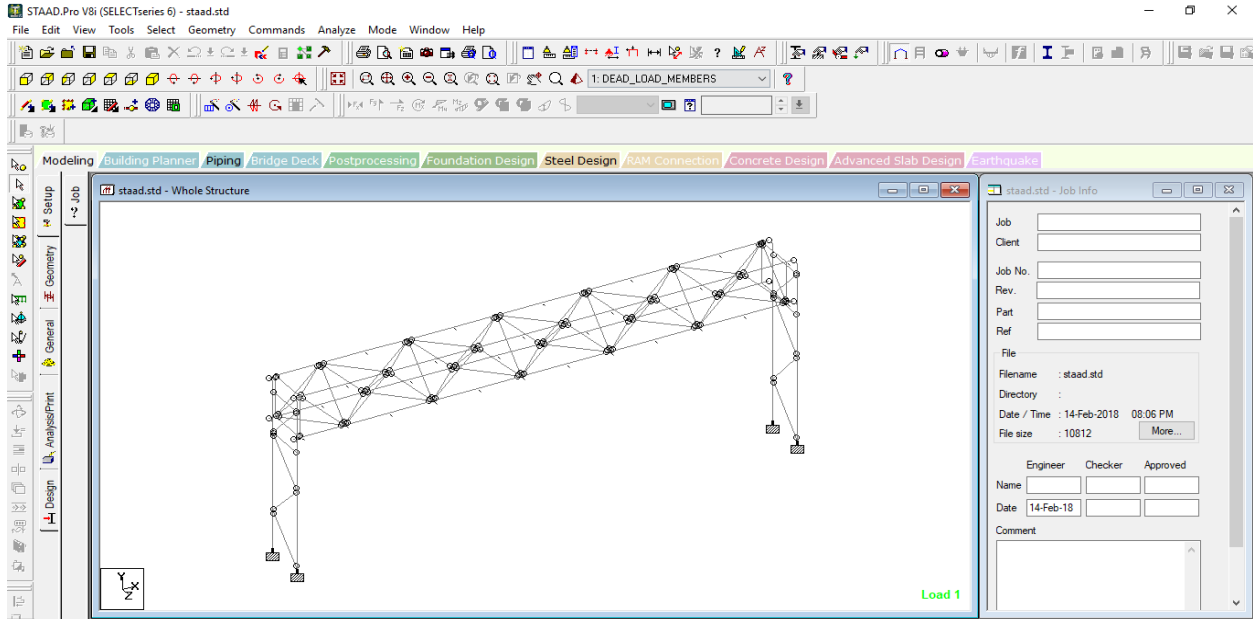
**Table 3.3: Repeated Speeds for the City of Manhattan (Only 0–10 mph Shown)**

Speed	Repeated Values	(HigSp*2 1600)	Speed	Repeated Values	(mediumSp*43200)	Speed	Repeated Values	(LowSp*2 1600)	Speed	(High+Medium+Low) Speeds
0	0	0.00E+00	0	45	1.94E+06	0	10424	2.25E+08	0	2.27E+08
1	0	0.00E+00	1	260	1.12E+07	1	580	1.25E+07	1	2.38E+07
2	0	0.00E+00	2	756	3.27E+07	2	1010	2.18E+07	2	5.45E+07
3	0	0.00E+00	3	1037	4.48E+07	3	832	1.80E+07	3	6.28E+07
4	30	6.48E+05	4	1605	6.93E+07	4	806	1.74E+07	4	8.74E+07
5	15	3.24E+05	5	1525	6.59E+07	5	755	1.63E+07	5	8.25E+07
6	90	1.94E+06	6	1607	6.94E+07	6	391	8.45E+06	6	7.98E+07
7	280	6.05E+06	7	1715	7.41E+07	7	535	1.16E+07	7	9.17E+07
8	471	1.02E+07	8	1605	6.93E+07	8	360	7.78E+06	8	8.73E+07
9	587	1.27E+07	9	1131	4.89E+07	9	210	4.54E+06	9	6.61E+07
10	831	1.79E+07	10	1080	4.67E+07	10	86	1.86E+06	10	6.65E+07

### 3.3 Using KDOT Sign Truss and STAAD.Pro Software to Generate Stresses

STAAD.Pro is a structural analysis and design computer program originally developed by Research Engineers International. This software was utilized to perform analysis on a structural model that was provided by KDOT to calculate structural member stresses. However, KDOT Sign Truss Interface was used for data entry in terms of the structural dimensions and a selected wind speed, as shown in Figure 3.5 and Figure 3.6. In correlation with STAAD.Pro, KDOT Sign Truss Interface (Figure 3.7) is simply a pre-processor to generate STAAD.Pro-based structural models. The main function of the Sign Truss Interface, besides generating the structural model, was to

simulate the wind pressure at any wind speed and generate and apply it to the sign(s) and structural members normal or transverse to the plane of the sign.



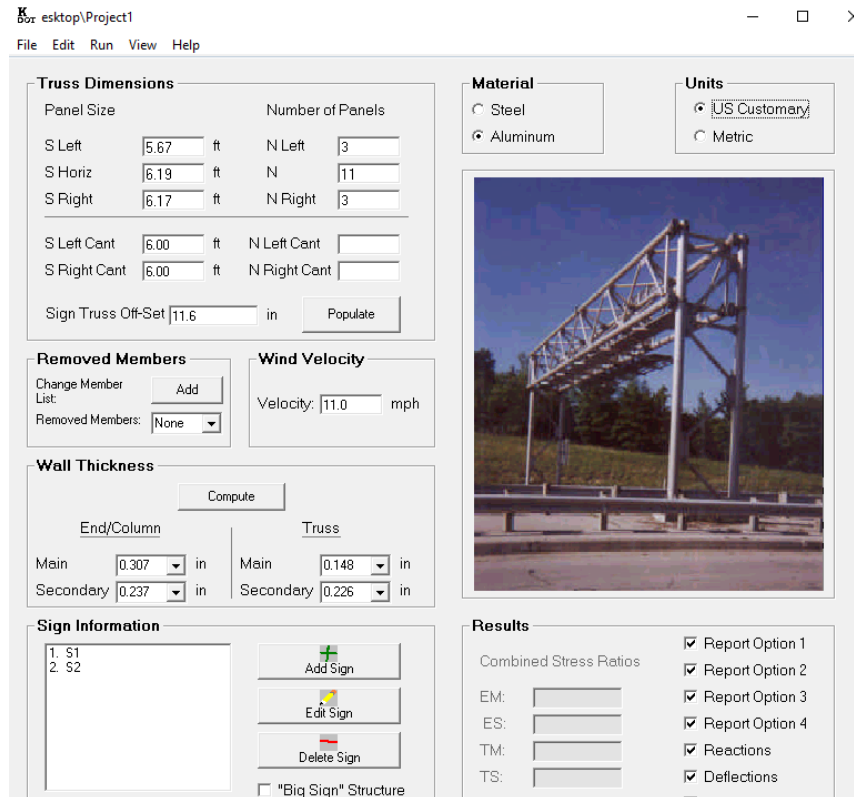
**Figure 3.5: Simulated Structural Model in STAAD.Pro as Generated by KDOT’s Sign Truss Interface**

This research used three simulated models to test, verify, and compare results. The first model drawn in AutoCAD is shown in Figure 3.6, which denotes the simulated structural model dimensions for structure members and signs. According to the figure: the horizontal truss span of the structure is 70’, sign 1 is 17’6” × 12’, and sign 2 is 15’6” × 6’6”. The model was drawn using AutoCAD to illustrate the structure and its dimensions more clearly. Figure 3.7 shows the Sign Truss Interface with all input data necessary to generate model 1. The first Sign Truss data fields are called “S left and S right,” referring to the spacing of nodes vertically at the two sides columns. The “N” is the number of bays in the vertical columns. Notice that the right side columns are taller than the left side columns. “S Horiz and N” are spacing of the nodes and number of spans in the horizontal truss, respectively. The horizontal offset from the columns is the distance by which the horizontal truss is shifted from the columns (given as 11.6” for Model 1). The Wind Speed field provides the speed value, so it can be converted into wind pressure. The Wall Thickness fields are categorized as End/Column and Truss, and each category is further divided into Main and Secondary. Main refers to elements with large diameter, such as columns and cord member

cylinders. Secondary refers to elements with small diameter, such as inclined or brace members. Finally, “Sign Information” refers to sign inputs used to calculate the wind pressure effect on them. Similarly, the Sign Truss Interface procedure was applied and followed for the other two models.



Figure 3.6: AutoCAD Drawing of Model 1 Structure and its Dimensions



**Figure 3.7: KDOT Sign Truss Interface with Model 1 Input Data**

Figure 3.8 is an AutoCAD drawing of model 2, which has larger dimensions than models 1 and 3. The horizontal truss span is 85 ft; the small sign is placed on the left and the larger sign is placed on the right. Model 2 tends to be more susceptible to wind than models 1 and 3, as the horizontal span is greater and more exposed to wind than the other two models. However, the vertical columns on both sides of the structures were identical for all the tested models. As shown in the figure, the small sign dimensions are 13'6" × 6' and the larger one is 18'6" × 9'. Figure 3.9 shows Sign Truss Interface having the input of model 2 as it was explained above in model 1.

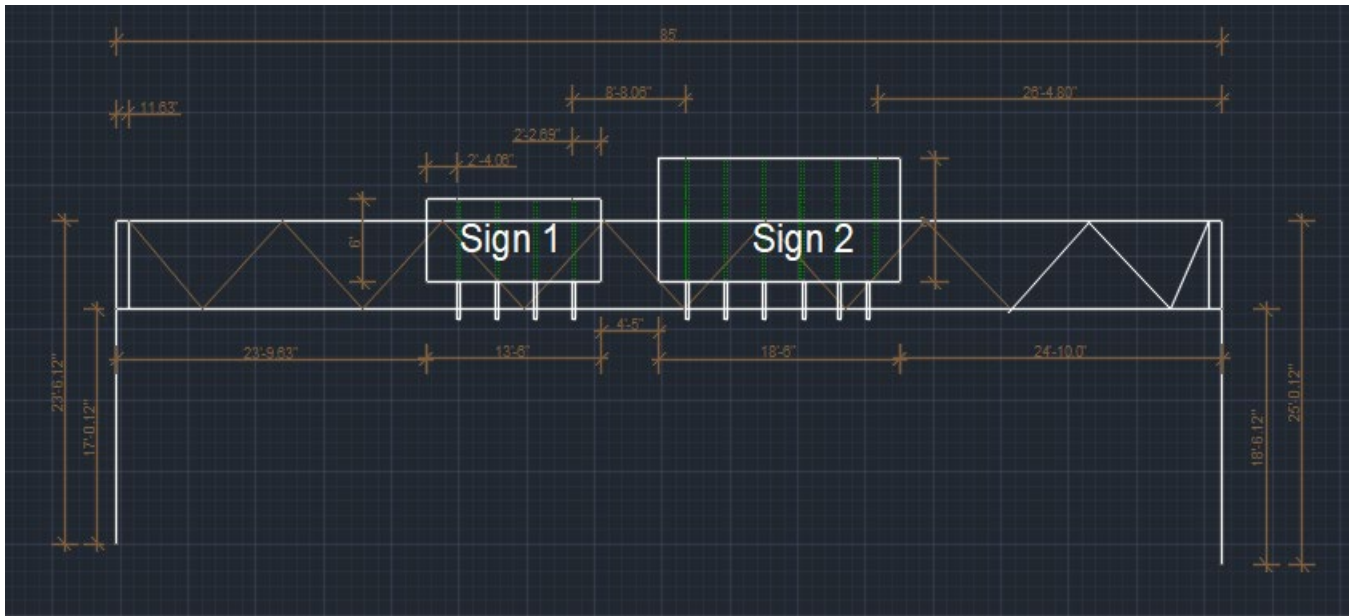


Figure 3.8: AutoCAD Drawing of Model 2 Structure and its Dimensions

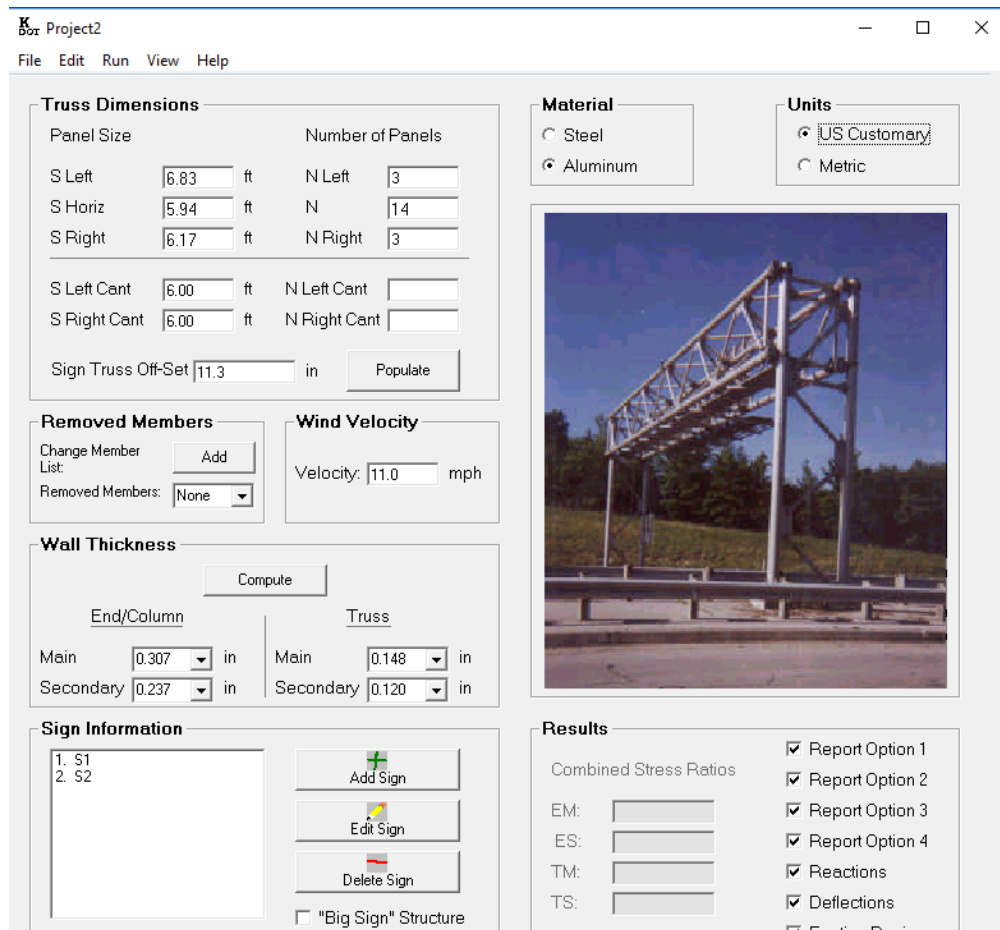
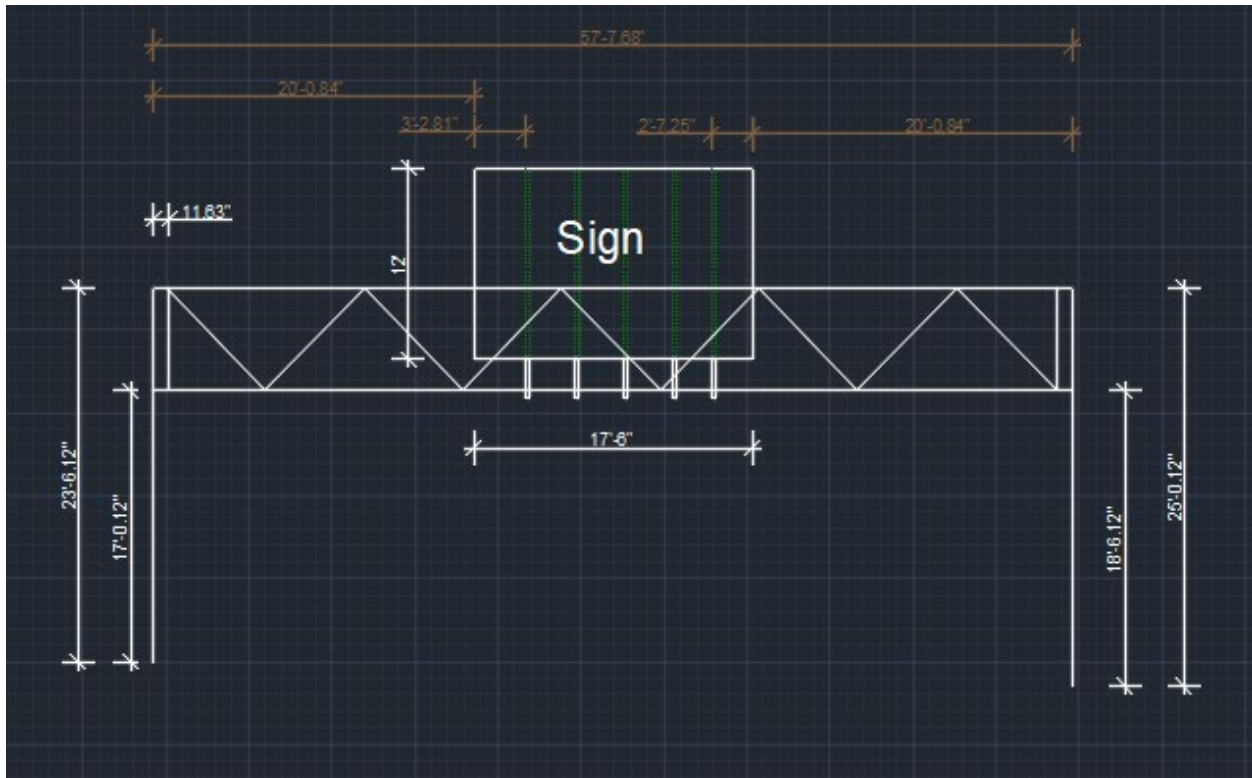


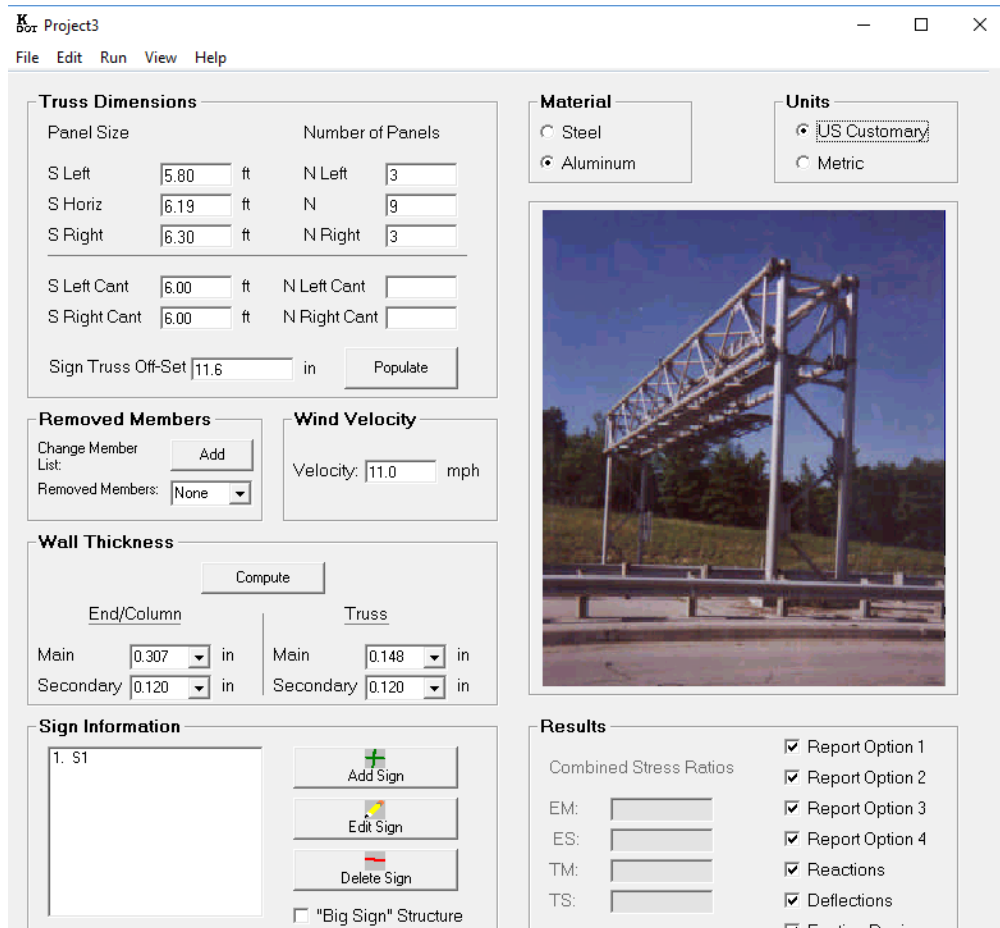
Figure 3.9: KDOT Sign Truss Interface with Model 2 Input Data

Figure 3.10 is an AutoCAD drawing of model 3 indicating structural details and model dimensions. As shown in the drawing, model 3 is shorter than the other two models and has only one overhead sign. The intent was to create a stiffer model which is less susceptible to wind compared to models 1 and 2. The horizontal truss span is 57'7.68" and the overhead sign dimensions are 17' 6" × 12'. Figure 3.11 shows the Sign Truss Interface with the input data of model 3. Natural Frequency Analysis was also conducted for all three models, and the fundamental frequencies, for mode 1, were found: Model 1 was 30.28 cycles/sec, Model 2 was 21.977 cycles/sec, and Model 3 was 32.476 cycles/sec.

The obtained natural frequency was significantly higher than the force and frequency of 1 Hz used in the ¼-day recurring model. No dynamic amplification factor was applied and static analysis was accordingly sufficient for the fatigue study.



**Figure 3.10: AutoCAD Drawing of Model 3 Structure and its Dimensions**



**Figure 3.11: KDOT Sign Truss Interface with Model 3 Input Data**

Sign Truss Interface, however, was a closed box and had no flexibility to introduce or perform additional analyses features. It was written to simulate wind pressure at a specific velocity, which was considered a limited data entry in this study. In other words, Sign Truss Interface is a quick available way to generate a STAAD.Pro model with its wind pressure loading by building STAAD.Pro text files. The text files could then be directly read by STAAD.Pro to process the model. In addition, the interface (Figures 3.7, 3.9, and 3.11) had only one entry option, velocity, for speed values, with no other method for automatically feeding 45 years' worth of data of high, medium, and low speeds. Therefore, an automated procedure called Successive Simulation Procedure (SSP) was created to apply the Sign Truss Interface to simulate wind pressures data that associated to each wind velocity. Data from the simulated wind pressures were fed to STAAD.Pro

to generate hundreds of successive simulations. STAAD.Pro calculated stresses for the structural members at every speed value that simulated wind pressure through Sign Truss Interface.

Highway sign trusses are regularly subjected to several types of loads including dead load, live load, wind load perpendicular to the plane of the structures and signs, and wind load transverse direction to the plane of the structures and signs. This research, however, applied wind speed perpendicular to the plane of the structural members and highway signs, and wind pressure transverse to the plane of the structural members and the highway signs. Because Sign Truss Interface cannot generate loading on members and signs for fatigue life, two AASHTO load cases were applied in this research to analyze structures based on directionality. Load case 1 consists of Normal wind load and Transverse wind load (Normal 1.0 Transverse 0.2), and load case 2 consists of Normal wind load and Transverse wind load (Normal 0.6 Transverse 0.3). Those load cases are based on the perpendicular load combination combining wind pressure on structural signs and members (e.g., load combination 17), and on the transverse load combination combining transverse wind pressure on structural signs and members (e.g., load combination 18). Furthermore, the two overall load combinations primarily facilitated the wind directionality dictated by AASHTO. The first overall load combination (load combination 19) represented AASHTO Load Case 1, which is composed of load combination. The second overall load combination (load combination 20) represented AASHTO load case 2, which is composed of load combination  $17 \times 0.6 + \text{load combination } 18 \times 0.3$ .

It is worth mentioning that the load combination 17 (fatigue life) consists of wind pressure load case number 4, which is perpendicular on the members, and wind pressure load case number 6, which is perpendicular on the signs, as shown in Figures 3.12 and 3.13. The load combination 18 (fatigue life) consists of transverse wind pressure of load case number 5, which blows on the structural members, and wind pressure load case number 7, which blows on the structural signs as shown in Figures 3.14 and 3.15. Therefore, output files of the interface were modified to accurately account for the performance using interface results to analyze any simulated structural model considering all load combinations' effects. This modification was made by removing all unnecessary load cases and adding only the load combination fatigue life number 17 for the perpendicular wind speed and load combination fatigue life number 18 for transverse wind



pressures. Then two load combinations were created using AASHTO ratios for wind load directionality as mentioned previously. This process was performed automatically using the Successive Simulation Procedure (SSP). For example, STAAD.Pro Editor displayed all load combinations except fatigue load combination numbers 17, 18, 19, and 20. After utilizing the automated procedure SSP to operate on Sign Truss Interface's output files and embed the fatigue load combination, STAAD.Pro analyzed the simulated structure using these load combinations to generate their respective member stresses. Once STAAD.Pro runs were complete, the SSP program extracted stresses due to fatigue load combinations from STAAD.Pro output files. STAAD.Pro works simultaneously with SSP to modify the extracted output data needed for fatigue life calculations of the structural members. Incorporating fatigue load combinations into STAAD.Pro software was significantly important because extracted stresses were caused by the effect of fatigue load combination. Once the stress results were all generated, the FLSS was launched to predict the number of consumed fatigue life as detailed below.

The FLSS program automatically saves stresses in Excel files in a new directory called "staad-anl-filtered-files." The new directory "staad-anl-filtered-files" is one of the key components that allows FLSS to perform fatigue life analysis. This directory contains all extracted Excel files pertaining to structural members and stresses according to effect of the fatigue load combinations. The other key component that is utilized by FLSS is a new directory called "signtruss-input-files." This directory is significant for the performance of FLSS because it has all the needed nodes that are associated with the structural members. These nodes are automatically extracted from STAAD.Pro software using FLSS because STAAD.Pro is unable to extract stresses as standalone output data or generate reports for external use. The nodes are extracted as text files as a part of other output components such as coordinate values, displacement values, and reaction support values. FLSS further uses the two directories "signtruss-input-files," which has all the needed nodes, and "staad-anl-filtered-files," which has all the needed stresses. FLSS extracts the nodes from "signtruss-input-files" directory and adds them to the "staad-anl-filtered-files" directory, so the Excel files in this directory have all the necessary stresses and nodes that correlate to each structural member. Chapter 5 includes more details about FLSS and its code functionality.

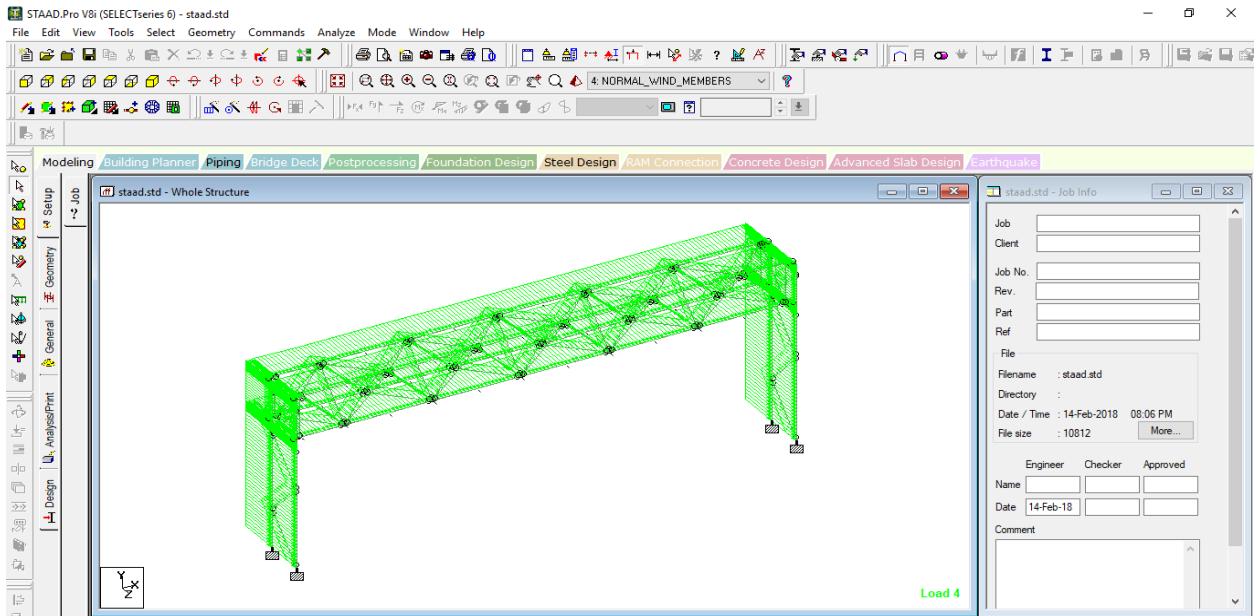


Figure 3.12: Wind Pressure Perpendicular to the Structure Span, Load Number 4

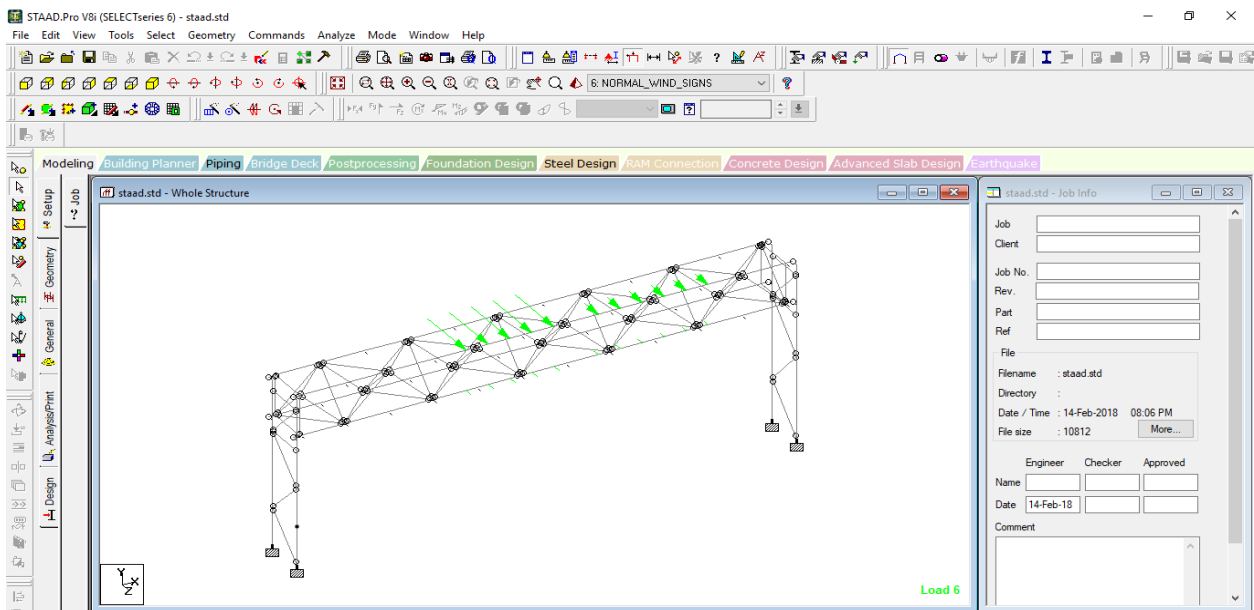
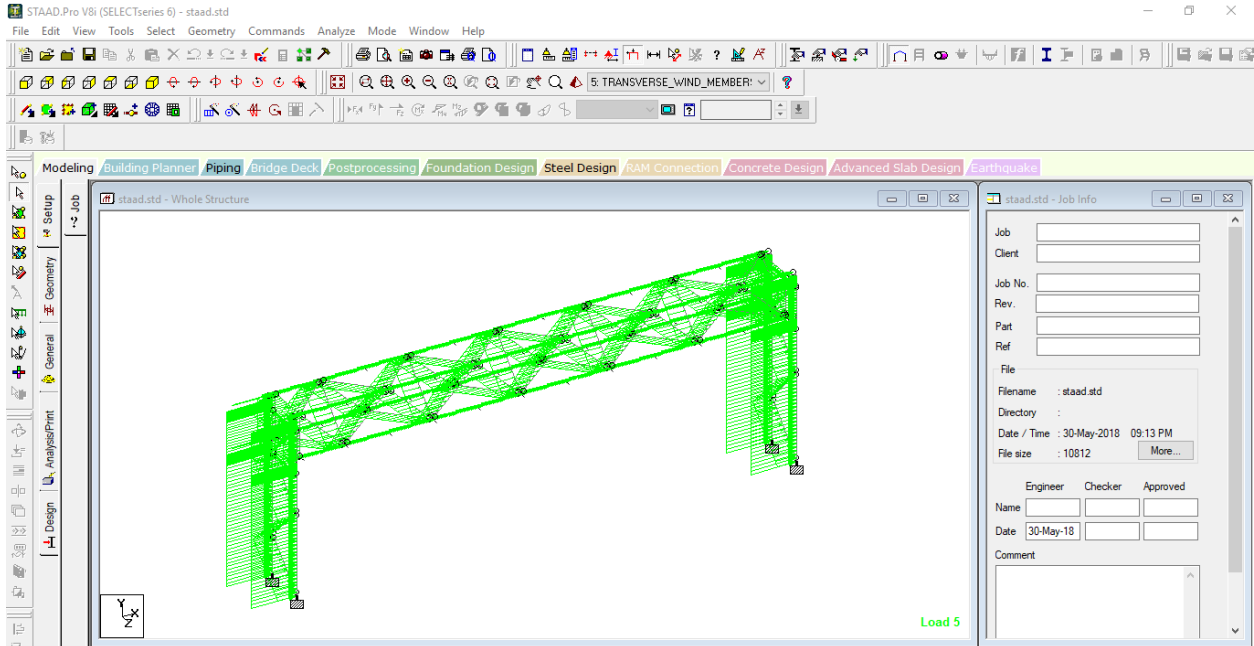
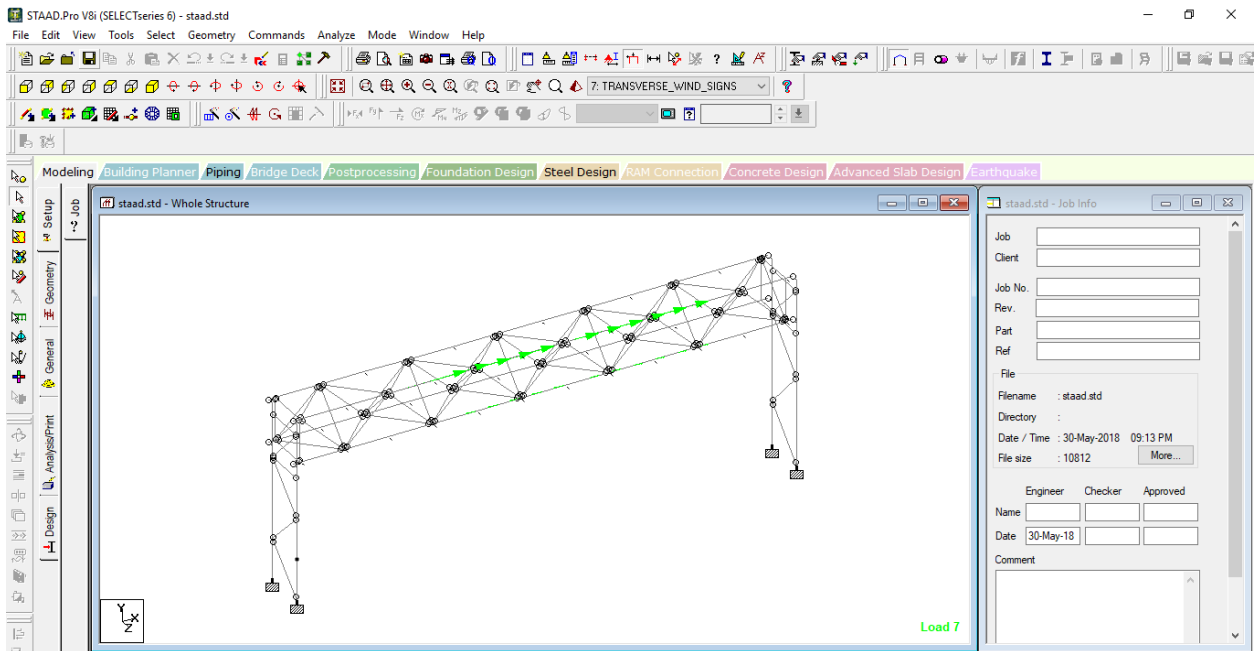


Figure 3.13: Wind Pressure Perpendicular to the Signs, Load Number 6



**Figure 3.14: Wind Pressure Transverse to the Members, Load Number 5**

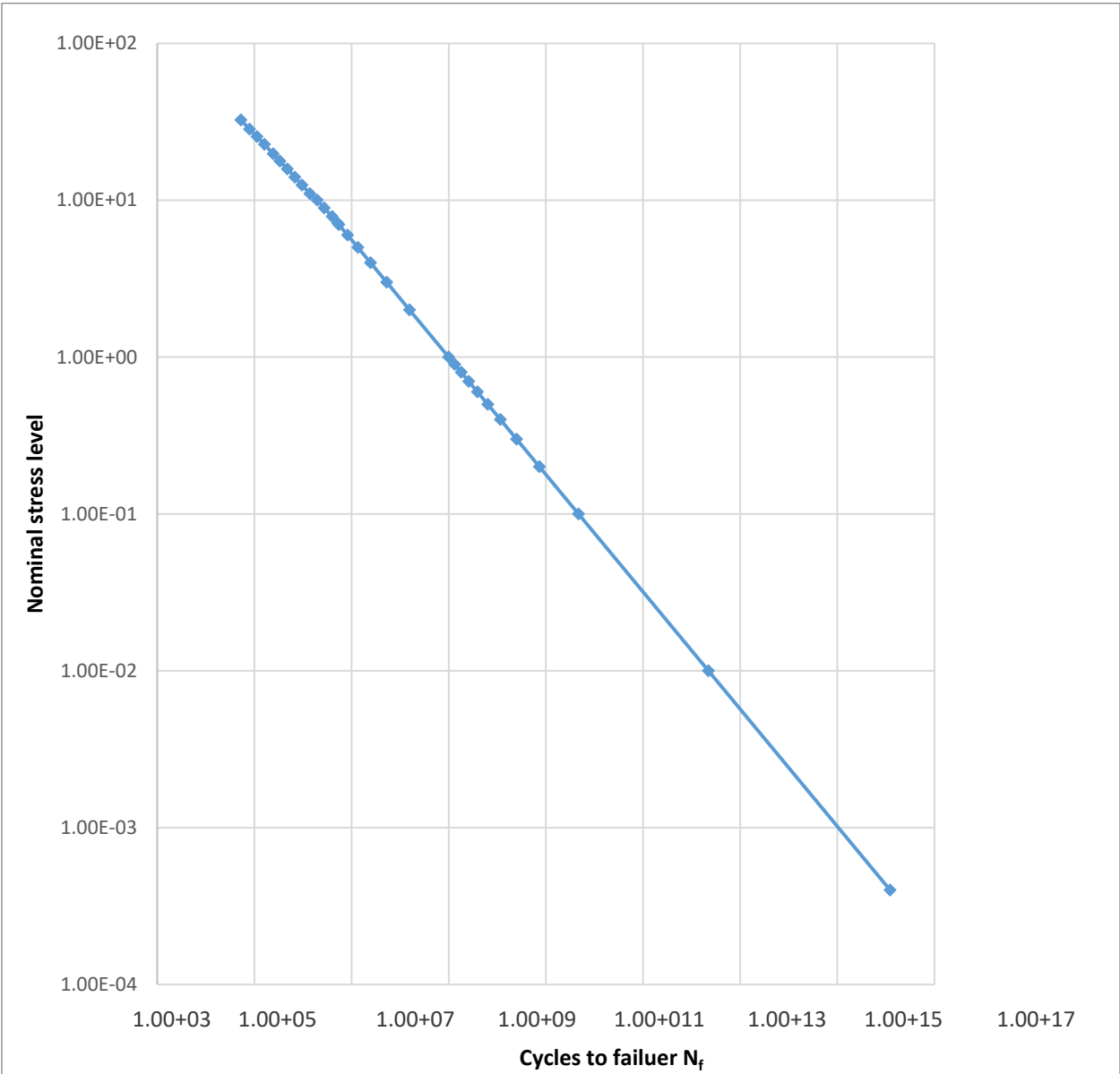


**Figure 3.15: Wind Pressure Transverse to the Signs, Load Number 7**

### 3.4 Categorized Stress Ranges for Fatigue Life

When the stress life analysis needs to query the S-N curve, almost certainly the data will not be available at the same stress point as the analysis has produced. Hence, the stress life analysis

needs to interpolate the S-N curve to find an appropriate value. The stress life analysis of each member gets calculated programmatically using log-log S-N curve, as shown in Figure 3.16. As shown in Figure 3.16, the slope is linear all the way to the lowest possible stress due to the fact that the structure is composed of welded aluminum material. Welded aluminum is known to have no threshold in its S-N curve, unlike steel structures where they have a threshold below which there is infinite life.



**Figure 3.16: S-N Curve for Stress Life Analysis of Welded Aluminum**  
Source: Sonsino (2007)

The S-N curve in Figure 3.16 was obtained as fatigue test result data from Sonsino (2007), as shown in Table 3.4. The obtained stresses were measured in MPa unit, and then were converted into ksi for the purpose of KDOT needs. The data were plotted after the conversion, so the nominal stresses measured by ksi were plotted on Y-axis and the number of cycles to failure were plotted on X-axis. However, the data as shown in Table 3.4 were not comprehensive as the lowest stress value was 7.13 ksi and its corresponding N-Cycles is 5.20E+06. The stresses in the structural models were expected to potentially be below 7.13 ksi. Therefore, mathematical interpolation process was conducted to reach the lowest possible stress values since the S-N curve is known to be linear in log-log scale all the way to lowest possible stresses with no threshold.

**Table 3.4: S-N Curve in Mpa and ksi Units**

N-cycles	Stress	
	Mpa	ksi
5.29E+04	2.24E+02	3.25E+01
7.90E+04	1.96E+02	2.84E+01
1.12E+05	1.76E+02	2.54E+01
1.61E+05	1.57E+02	2.27E+01
2.43E+05	1.36E+02	1.98E+01
3.35E+05	1.23E+02	1.78E+01
4.77E+05	1.09E+02	1.58E+01
6.79E+05	9.68E+01	1.40E+01
9.53E+05	8.61E+01	1.25E+01
1.38E+06	7.60E+01	1.10E+01
1.96E+06	6.91E+01	1.00E+01
2.74E+06	6.16E+01	8.92E+00
3.97E+06	5.44E+01	7.89E+00
5.20E+06	4.92E+01	7.13E+00

Source: Sonsino (2007)

Table 3.5 lists all fatigue stress and N-cycle values including values extrapolated below 7.13 ksi, until a stress value near zero. Since the plot is in log-log scale, the zero stress value corresponds to an infinite number of cycles.

**Table 3.5: N-Cycles Versus Fatigue Stresses Including Lower Stress Levels**

N-cycles	Stresse
5.29E+04	3.25E+01
7.90E+04	2.84E+01
1.12E+05	2.54E+01
1.61E+05	2.27E+01
2.43E+05	1.98E+01
3.35E+05	1.78E+01
4.77E+05	1.58E+01
6.79E+05	1.40E+01
9.53E+05	1.25E+01
1.38E+06	1.10E+01
1.96E+06	1.00E+01
2.74E+06	8.92E+00
3.97E+06	7.89E+00
5.20E+06	7.13E+00
5.48E+06	7.00E+00
8.27E+06	6.00E+00
1.35E+07	5.00E+00
2.45E+07	4.00E+00
5.28E+07	3.00E+00
1.56E+08	2.00E+00
9.96E+08	1.00E+00
1.32E+09	9.00E-01
1.81E+09	8.00E-01
2.59E+09	7.00E-01
3.91E+09	6.00E-01
6.36E+09	5.00E-01
1.15E+10	4.00E-01
2.49E+10	3.00E-01
7.37E+10	2.00E-01
4.71E+11	1.00E-01
2.22E+14	1.00E-02
1.22E+18	4.00E-04
2.63E+18	3.00E-04
7.77E+18	2.00E-04
4.96E+19	1.00E-04
∞	0.00E+00

Non-cantilevered aluminum structural supports for highway signs, luminaires, and traffic signals are susceptible to statically induced stresses because natural wind fluctuation and stress levels are related to the amplitude and fluctuation of wind speeds. Once stress values are calculated

through STAAD.Pro software and are extracted in the form of a list of stress ranges, then stress ranges are linked to corresponding N-cycles.

Once the stresses are determined with their corresponding N-cycles for each structural member, they are linked to their number of repetitions related to corresponding wind speeds. Naturally, the ratio of actual repetitions to the ultimate N-cycles represents the amount of accumulated damage for any corresponding stress. However, in order to incorporate conservatism into the fatigue life estimation to account for phenomena such as truck-induced vibration, stresses were divided into ranges of 1 ksi each, and accumulated damage of each stress range was found by normalizing all repetitions under that stress range using conservative N-cycles. This conservative N-Cycles value was selected here to correspond to the highest stress in that range yielding the lowest N-cycles for the same range.

Table 3.6 clarifies how the data were calculated mathematically. The table represents data for the city of Chanute for member 5 only, as an example. The Speed column contains all speed values for this city over the 45-year time period. The Stress column shows all stresses to which member number 5 was subjected, and the N-cycles column shows their corresponding ultimate cycles. The Repeated Speed column lists all repeated cycles that correspond to each speed value. The table illustrates how the ksi ranges (stress ranges) were assigned. For example, 1 ksi is the stress range 0–0.999, so the highest value from Table 3.6 within stress range 1 ksi is 0.897 and the corresponding N-cycles taken to determine fatigue life is 1.81E+09. The same process is applied for 2 ksi, 3 ksi, 4 ksi, 5 ksi, etc.

The higher the stress values, the lower their corresponding N-cycles. S-N curve for welded aluminum has a linearly negative slope in a log-log scale. In other words, when a member is subjected to high stress, constant cycling causes the member to fatigue rapidly, thus, decreasing the service life of the member. Because each member has a unique set of stresses due to variability of the wind effect, stress ranges and corresponding N-cycles must be determined individually to be applied in Miner's rules for fatigue life estimation; refer to Section 3.5 for more details about fatigue life evaluation.

**Table 3.6: Parameters for Member 5 in Model 1 in Chanute**

Speed	Stresses	N-cycles	Repeated Speeds
1	0.000	7.77E+18	2.71E+07
2	0.003	1.22E+18	3.68E+07
3	0.005	1.22E+18	4.46E+07
4	0.009	1.22E+18	5.87E+07
5	0.013	2.20E+14	6.31E+07
6	0.02	2.20E+14	7.03E+07
7	0.028	2.20E+14	8.49E+07
8	0.036	2.20E+14	8.54E+07
9	0.045	2.20E+14	9.16E+07
10	0.056	2.20E+14	9.76E+07
11	0.068	2.20E+14	6.96E+07
12	0.081	2.20E+14	8.12E+07
13	0.095	2.20E+14	6.03E+07
14	0.11	4.71E+11	6.95E+07
15	0.126	4.71E+11	5.62E+07
16	0.144	4.71E+11	4.13E+07
17	0.162	4.71E+11	4.94E+07
18	0.181	4.71E+11	3.89E+07
19	0.202	7.73E+10	4.86E+07
20	0.225	7.73E+10	3.27E+07
21	0.247	7.73E+10	2.62E+07
22	0.271	7.73E+10	1.49E+07
23	0.297	7.73E+10	1.79E+07
24	0.323	7.73E+10	8.32E+06
25	0.35	7.73E+10	7.78E+06
26	0.397	7.73E+10	7.04E+06
27	0.408	7.73E+10	6.48E+05
28	0.439	7.73E+10	5.40E+06
29	0.471	7.73E+10	6.16E+06
30	0.504	6.36E+09	2.59E+06
31	0.539	6.36E+09	2.59E+06
32	0.573	6.36E+09	6.48E+05
33	0.61	6.36E+09	9.72E+05
35	0.686	6.36E+09	3.24E+05
36	0.726	6.36E+09	3.24E+05
37	0.767	6.36E+09	6.48E+05
39	0.853	6.36E+09	3.24E+05
40	0.897	6.36E+09	3.24E+05
46	1.185	9.96E+08	3.24E+05
47	1.1238	9.96E+08	3.24E+05
51	1.4574	9.96E+08	3.24E+05
63	2.239	1.56E+08	6.48E+05



### 3.5 Procedure for Estimating the Remaining Fatigue Life (Miner's Rule)

Miner's rule is a mathematical formula that was introduced in 1945 by M. A. Miner for expressing a structural cumulative fatigue damage. The fatigue damage is represented through the following formula:

$$D = \sum(n_i/N_{fi})$$

Where:

$D$  = accumulated damage,

$n_i$  = the applied number of cycles for each wind speed (or stress level), and

$N_{fi}$  = the total number of cycles to failure under the same constant-amplitude stress level that corresponds to examined wind speed.

If an object can tolerate a certain amount of damage,  $D$ , then the object is subject to failure if it experiences damages more than 1.  $D$  must be either  $\geq 1$  which is the case of failure, or  $< 1$  which is the fraction of used up fatigue life to failure. The result ratio number 1 is the threshold or the breaking point where the fatigue life is referred to. Also, the fatigue life results are color coded, as shown in Chapter 4, for easier identification:

Fatigue life  $< 0.8$  Green color

$0.8 \leq$  Fatigue life  $< 1$  Yellow color

$1 \leq$  Fatigue life  $< 1.1$  Light Brown color

Fatigue life  $> 1.1$  Red color

## Chapter 4: Results and Discussion

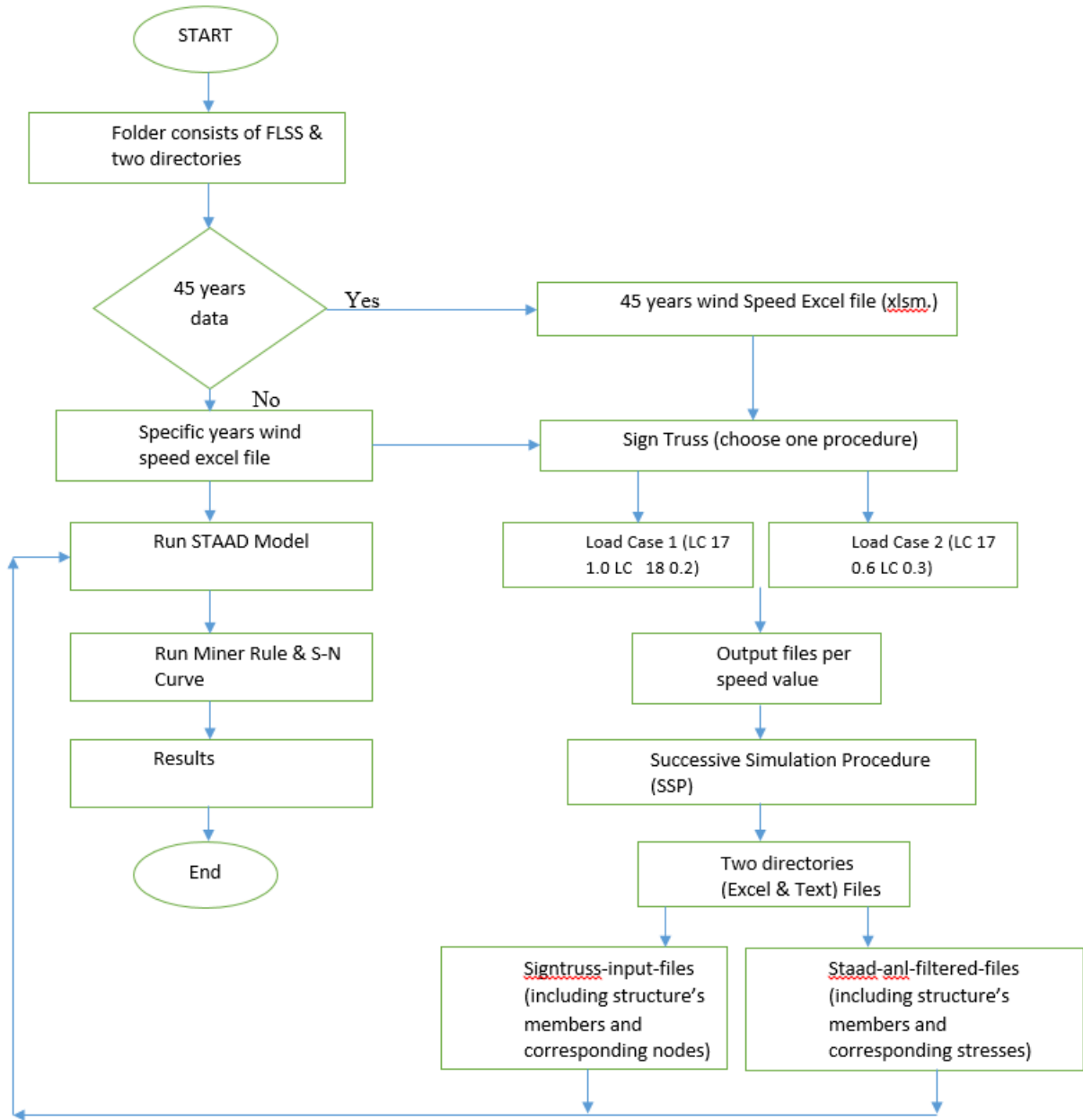
Fatigue is a cumulative damage process caused by repeated application of loads, resulting in cracking and possible rupture of member connections. Fatigue failures can occur at applied stress levels much lower than the tensile strength of a given material. Fatigue cracks form and propagate from weld discontinuities and/or stress concentrations when a structural member is subjected to significant cyclic live loads (Yan, Dyke, & Irfanoglu, 2012). When structural members are tested, the loading is typically described in relation to nominal stress in the loaded member apart from the weld detail. The design of sign and signal structures to promote fatigue resistance is routinely based on criteria outlined in the AASHTO *Standard Specifications for Highway Bridges*.

Highly variable fatigue data generally consist of the number of cycles to fatigue failure for structure details subjected to a constant amplitude stress range. Small cracks may form when a structure or a structural component is repeatedly subjected to stresses below the allowable stress of aluminum structural material. Continued cyclic loading may cause these cracks to propagate, leading to failure. Fatigue cracks tend to form in regions of stress concentration, such as notches, holes, welds, or other discontinuities. Although structures are typically subjected to complex loading, amplitude sinusoidal loading is often used to characterize the fatigue life of components and connections. As mentioned, the fatigue life of aluminum structures at various stress ranges can be represented by S-N curve (where S is the stress ranges and N is the number of loading cycles to failure). A point on the S-N plot indicates the number of cycles a component or connection can sustain at a given stress range prior to ultimate failure. The cycle count in the plot is the sum of the number of cycles required to initiate the crack and the number of cycles to propagate the crack to failure (Gilani & Whittaker, 2000). However, Miner's rule most accurately predicts fatigue life for structures subjected to variable loading history.

The flow-chart in Figure 4.1 illustrates the deterministic approach process including the folder that runs FLSS, and necessary directories, such as Fatigue Life, NCyclesAndRepeatedSpeeds, signtruss-input-files, and staad-anl-filtered-files. The first directory, which is Fatigue Life, is the directory where all the fatigue life results of member numbers were

generated and saved. The results are presented in the format of an Excel file (.xlsx or .xlsm), where the Excel file shows member numbers and their corresponding fatigue life results. Also, the Excel file contains the fatigue life results color codes for easy identification. The second directory, NCyclesAndRepeatedSpeeds, consists of ncycles.xlsx, speeds.xlsm, and repeated speeds text files. The ncycles.xlsx file has an S-N curve graph and its data (i.e., stresses and corresponding N-cycles). The speeds.xlsm file contains all the data from the 45-year data collection period. FLSS uses this data to calculate speeds and corresponding repeated speeds based on the selected year. When an FLSS user selects a city, year built, and number of years the structure has been in service, a new set of calculated speeds and their corresponding repeated speeds are calculated and displayed in the speeds.xlsm file. Once these results are displayed in speeds.xlsm, the selected city's correlated text file of repeated speeds is updated. These text files with updated repeated speeds are contained in the repeated speeds text files of the NCyclesAndRepeatedSpeeds directory. Each of the eight text files belongs to a city, and the repeated speeds in each text file are changeable according to the selected city, year built, and number of years the structure has been in service.

The other two directories in the FLSS folder are “signtruss-input-files” and “staad-anl-filtered-files.” The “signtruss-input-files” directory contains all text files with structure member numbers and corresponding nodes, while the “staad-anl-filtered-files” directory contains Excel files that have the structure's member numbers and their corresponding stresses. Each Excel file has a Results sheet that lists structure members and their corresponding stresses due to fatigue effect. The Results sheets, which are generated and added to the Excel files via FLSS, contain extracted stresses per each member number. FLSS relies on the four directories, Fatigue lives, NCyclesAndRepeatedSpeeds, “signtruss-input-files,” and “staad-anl-filtered-files,” to calculate structure members' fatigue life because these directories have all the necessary information the software needs. The flow chart in Figure 4.1 is created to help FLSS users to track the process of calculating fatigue lives and identify how the software functions harmoniously with its necessary helping directories.

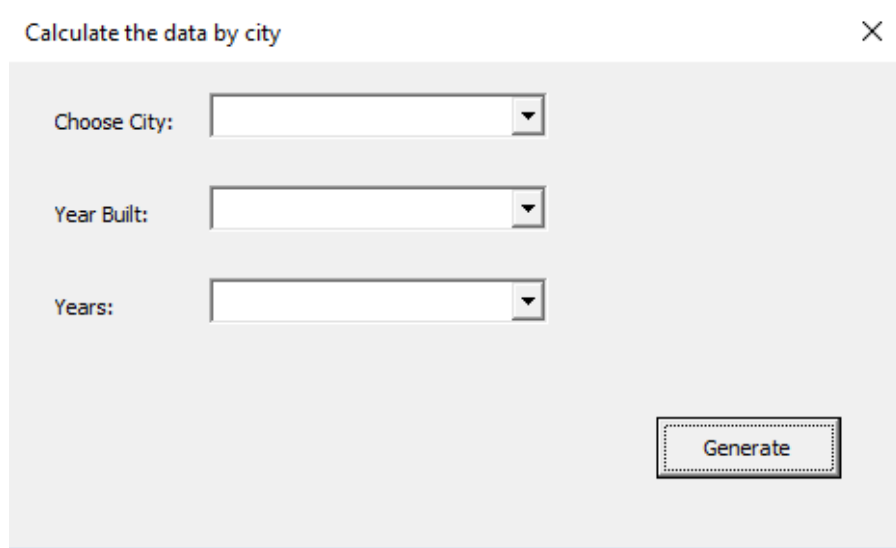


**Figure 4.1: Deterministic Approach Flow Chart**

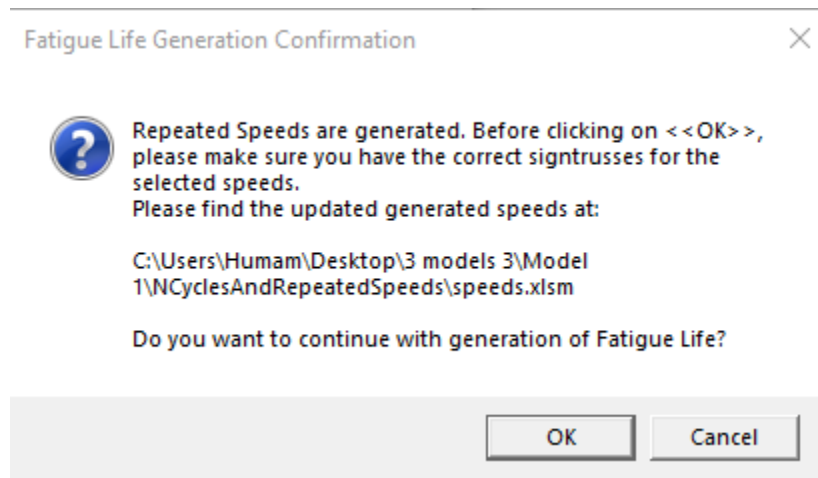
Figure 4.2 shows the Fatigue Life Simulator Software interface. The first drop-down button selection, “Choose City,” displays the eight cities representing the eight regions in Kansas: Chanute, Dodge City, Garden City, Goodland, Hill City, Manhattan, Topeka, and Wichita. The second drop-down button selection, “Year Built,” lists the years of data collection from 1975 to 2019, so FLSS users can select the year in which a certain structure was built. The third drop-down button selection, “Years,” represents a structure’s years of service. For example, FLSS users can

select a city, such as Manhattan, from “Choose City” to run an analysis, then select the year a structure was built, like 1985, and then from “Years” select the number of years a structure has been in service, such as 15 years. Then the user must click the “Generate” button to generate fatigue life results of each member. Once the software runs, a message is displayed that asks users if they want to continue generating fatigue life (Figure 4.3). Users then can decide to calculate fatigue life, or close out of the message window. If users select the “Cancel” button because they want to find corresponding stresses of the year built and year in service, then they must select the Speed.xlsm text file in the “NCyclesAndRepeatedSpeeds” directory to find the speed values that correlate to the selected years, in order to identify new stresses. Stresses are found by inputting speed values into the Sign Truss Interface and finding their corresponding input files. These input files are then used in one of the two procedures indicated in the flow chart in Figure 4.1, Load Case 1 Wind Procedure and Load Case 2 Wind Procedure. Load Case 1 and Load Case 2 wind procedure are the procedures that use perpendicular and transverse wind effect based on AASHTO recommended ratios.

The user message shown in Figure 4.3 also indicates the path of the speed.xlsm text file for easy user access. The speed values and corresponding repeated speeds are changeable every time users select “Year built” and “Years” options. Once speed values are generated, users can run the Sign Truss Interface to generate input files that correlate to each speed value, as indicated in the Figure 4.1 flow chart. The flow chart illustrates the process steps of finding fatigue life. The input files are then collected and input into the SSP, and once the procedure runs, two directories named “signtruss-input-files” and “staad-anl-filtered-files” are generated. These two directories are moved to “Folder consists of FLSS & its directories.” FLSS uses these two directories to find fatigue life. In other words, every time users want to run FLSS, they must go through the procedure indicated in the flow chart in Figure 4.1 in order to obtain fatigue life. This procedure is applicable to all eight cities.



**Figure 4.2: Fatigue Life Simulator Software (FLSS)**



**Figure 4.3: User Message for Generating Speed Values**

Magnitude 1 is the threshold value of fatigue life that Miner's rule represents. This value indicates structure member behavior as it relates to remaining life span. These values are color-coded and categorized to help users determine next-step actions. For example, fatigue life results below value 0.8 were identified as green. Fatigue life results greater than or equal to 0.8 and less than 1 were identified as yellow. Fatigue life results greater than or equal to 1 and less than 1.1 were identified as light brown. Fatigue life results above 1.1 were identified as red. This color-coded approach helps FLSS users quickly identify members that need immediate attention. Color-coded fatigue life results from each city are presented in Tables 4.1, 4.2, and 4.3. Table 4.1

highlights member fatigue life results for Manhattan (northeast region). Manhattan from the Northeast region is chosen to examine its highway sign trusses aluminum structures fatigue failure due to stress, so Miner Rule method is programmatically predicting the fatigue life of the structures' members. Also, Manhattan was selected to discuss its fatigue value results because it is similar to the other cities as far as the nature of members' results being under the threshold Miner rule. Tables 4.1, 4.2, and 4.3 are the fatigue life results for load case 1 of model 1; refer to fatigue life results for model 2 and model 3 in Appendix B, which is available separately upon request.

**Table 4.1: Miner's Rule Results for Only 12 Members of Model 1 in City of Manhattan**

Member	Fatigue Life	
5	9.09E-01	Yellow
6	3.07E-01	Green
7	9.04E-01	Yellow
8	3.07E-01	Green
9	9.04E-01	Yellow
10	3.05E-01	Green
11	1.59E-02	Green
12	3.05E-01	Green
13	5.26E-06	Green
14	1.88E-01	Green
15	5.26E-06	Green
16	5.26E-06	Green

Table 4.1 data shows a fatigue life result of 0.30 for member 6, a ratio result of the amount of damage the member has experience due to fatigue. Therefore, the member has a remaining life of only 0.70 to reach failure indicating that this member has experienced damage, but the amount of damage is not severe. In contrast, the fatigue life results for member number 5 is 0.90, revealing a high amount of deterioration throughout its years of service, and a remaining fatigue life of only 0.1 to reach 1 (threshold to failure). This result indicates to inspectors that this member requires immediate attention since the member is nearing the end of its fatigue life. Nevertheless, at the same city (Table 4.1), other structure members do not experience high stresses and so have infinite life and do not require fatigue inspection. For example, member number 13 has a fatigue life of

5.26E-6, which means the amount of deterioration is so minimal that its life is almost infinite, indicating to inspectors that this member does not need a fatigue inspection.

Tables 4.2 and 4.3 show fatigue life results for load case 1 of model 1; fatigue life results for model 2 and model 3 are presented in Appendix B. Results from Dodge City and Garden City (Table 4.2) indicate occurrences in which structure members' values exceeded Miner's rule threshold. For example, fatigue life results for member numbers 5 at Dodge City and Garden City are 1.01 and 0.99, respectively, indicating that these members most likely have no remaining life and must be inspected. Member 9 in Dodge City shows a fatigue life value of 0.51, requiring minimal attention since the value of remaining life is 0.49 percent ratio. In comparison, member 9 in Garden City has a fatigue life value of 0.99, requiring extra attention since the value of remaining life is only 0.1. Members 15 in Dodge City and Garden City have fatigue life values of 5.97E-06 and 5.73E-06, respectively, which means their members likely have infinite life, and no fatigue life inspection is required. However, several members shown in the full tables sets in Appendix A exceed 1, and most likely have no remaining lives. Tables 4.2 and 4.3 indicate that aluminum structures in Dodge City and Garden City are more prone to stresses and fatigue failure than the other studied cities, such as Hill City, Manhattan, Topeka, Chanute, Wichita, and Goodland. Table 4.3 shows the fatigue life of the latter cities for only 12 members; refer to a complete set of the tables in appendix A.

Dodge City member number 9 has fatigue life of 0.51, which means less attention is needed as the member has 0.49 percent ratio remaining life. In comparison, Garden City member number 9 has a fatigue life result of 0.99, which means extra attention is required as the remaining life is only 0.1. Member number 15 at both Dodge City and Garden City have fatigue life 5.97E-06 and 5.73E-06, respectively, which means most likely their members both have infinite life and there is no fatigue life inspection required.

Table 4.4 shows fatigue life results for load case 2, which represents load combination 19 (LC 17 0.6 LC 18 0.3). These table were from model 1 only; refer to table fatigue life results for model 2 and model 3 in Appendix B. Member number 5 from the Manhattan table has fatigue life 0.18, which means it had a long-life span versus member number 8, which has 0.90, or a short life span. Dodge City member number 5 has fatigue life result as 1.01, which means it is most likely



failing. Member number 8 in Dodge City, however, has 0.34 and that indicates having a long life span. Member numbers 15 and 16, respectively, in all eight cities have infinite life span.

**Table 4.2: Miner’s Rule Results of Dodge City and Garden City for Only 12 Members**

Member	Fatigue Life		Member	Fatigue Life	
5	1.02E+00	Orange	5	9.97E-01	Yellow
6	1.02E+00	Orange	6	9.93E-01	Yellow
7	5.20E-01	Green	7	9.90E-01	Yellow
8	1.02E+00	Orange	8	9.93E-01	Yellow
9	5.20E-01	Green	9	9.90E-01	Yellow
10	5.39E-02	Green	10	7.23E-01	Green
11	2.82E-03	Green	11	1.73E-02	Green
12	5.39E-02	Green	12	7.23E-01	Green
13	5.97E-06	Green	13	2.71E-03	Green
14	5.39E-02	Green	14	5.06E-01	Green
15	5.97E-06	Green	15	5.73E-06	Green
16	5.97E-06	Green	16	2.71E-03	Green

**Dodge City**

**Garden City**

**Table 4.3: Miner’s Rule Results for Chanute, Goodland, Hill City, Topeka, and Wichita**

Member	Fatigue Life		Member	Fatigue Life		Member	Fatigue Life	
5	9.65E-01	Yellow	5	9.86E-01	Yellow	5	9.72E-01	Yellow
6	9.61E-01	Yellow	6	9.85E-01	Yellow	6	9.68E-01	Yellow
7	4.91E-01	Green	7	7.19E-01	Green	7	9.66E-01	Yellow
8	9.61E-01	Yellow	8	9.85E-01	Yellow	8	9.68E-01	Yellow
9	4.91E-01	Green	9	7.19E-01	Green	9	9.66E-01	Yellow
10	2.00E-01	Green	10	1.13E-01	Green	10	7.05E-01	Green
11	2.64E-03	Green	11	2.71E-03	Green	11	1.69E-02	Green
12	2.00E-01	Green	12	1.13E-01	Green	12	7.05E-01	Green
13	5.59E-06	Green	13	5.74E-06	Green	13	2.65E-03	Green
14	1.10E-01	Green	14	5.22E-02	Green	14	4.93E-01	Green
15	5.59E-06	Green	15	5.74E-06	Green	15	5.62E-06	Green
16	5.59E-06	Green	16	5.74E-06	Green	16	2.65E-03	Green

**Chanute**

**Goodland**

**Hill City**

Member	Fatigue Life		Member	Fatigue Life	
5	9.03E-01	Yellow	5	9.67E-01	Yellow
6	3.05E-01	Green	6	9.65E-01	Yellow
7	1.03E-01	Green	7	3.27E-01	Green
8	3.05E-01	Green	8	9.65E-01	Yellow
9	1.03E-01	Green	9	3.27E-01	Green
10	1.62E-02	Green	10	2.00E-01	Green
11	5.24E-06	Green	11	2.65E-03	Green
12	1.62E-02	Green	12	2.00E-01	Green
13	5.24E-06	Green	13	5.61E-06	Green
14	2.54E-03	Green	14	1.10E-01	Green
15	5.24E-06	Green	15	5.61E-06	Green
16	5.24E-06	Green	16	5.61E-06	Green

**Topeka**

**Wichita**

**Table 4.4: Fatigue Life Results of Load Case 2 for the Eight Cities**

Member	Fatigue Life	Member	Fatigue Life	Member	Fatigue Life
5	1.89E-01	5	1.02E+00	5	9.93E-01
6	9.04E-01	6	3.44E-01	6	7.23E-01
7	6.59E-01	7	1.16E-01	7	3.35E-01
8	9.04E-01	8	3.44E-01	8	7.23E-01
9	6.59E-01	9	1.16E-01	9	3.35E-01
10	4.69E-02	10	1.80E-02	10	1.10E-01
11	2.48E-03	11	5.97E-06	11	1.73E-02
12	4.69E-02	12	1.80E-02	12	1.10E-01
13	5.26E-06	13	5.97E-06	13	5.73E-06
14	4.69E-02	14	2.82E-03	14	1.10E-01
15	5.26E-06	15	5.97E-06	15	5.73E-06
16	5.01E-06	16	5.81E-06	16	5.59E-06

**Manhattan**

**Dodge City**

**Garden City**

Member	Fatigue Life	Member	Fatigue Life	Member	Fatigue Life
5	9.61E-01	5	9.85E-01	5	4.95E-01
6	3.25E-01	6	5.03E-01	6	7.05E-01
7	4.91E-01	7	2.04E-01	7	3.27E-01
8	3.25E-01	8	5.03E-01	8	7.05E-01
9	4.91E-01	9	2.04E-01	9	3.27E-01
10	4.98E-02	10	1.73E-02	10	1.08E-01
11	2.64E-03	11	2.71E-03	11	1.69E-02
12	4.98E-02	12	1.73E-02	12	1.08E-01
13	5.59E-06	13	5.74E-06	13	5.62E-06
14	1.68E-02	14	1.73E-02	14	1.08E-01
15	5.59E-06	15	5.74E-06	15	5.62E-06
16	5.42E-06	16	5.61E-06	16	5.46E-06

**Chanute**

**Goodland**

**Hill City**

Member	Fatigue Life	Member	Fatigue Life
5	1.88E-01	5	7.04E-01
6	1.03E-01	6	2.01E-01
7	1.62E-02	7	4.93E-01
8	1.03E-01	8	2.01E-01
9	1.62E-02	9	4.93E-01
10	2.48E-03	10	5.00E-02
11	5.24E-06	11	2.65E-03
12	2.48E-03	12	5.00E-02
13	5.24E-06	13	5.61E-06
14	2.48E-03	14	1.69E-02
15	5.24E-06	15	5.61E-06
16	5.02E-06	16	5.47E-06

**Topeka**

**Wichita**

## 4.1 Procedure for Obtaining Fatigue Life Results

The following procedure can be used to obtain fatigue life results for a specific city:

1. Run Fatigue Life Simulator Software (FLSS) after inputting all the desired inputs. A message will be displayed asking if users would like to continue or stop and use speed values. If users choose “No,” this means users must follow the file path the message displays to obtain speed values. The software will display a list of speed values in the form of text files. These speed values are the results of users’ selections.
2. Use the speed values one by one by inputting them into Sign Truss Interface. Each speed value will result in generating a model in STAAD.Pro with results.
3. Go to STAAD.Pro Editor icon and press it to display results. These results are the specified model’s details.
4. From the STAAD Editor’s window, go to “Send in email” to generate the model’s details in STAAD.Pro extension. Save the file in a “txt” extension, and follow the same process for all speed values.
5. Gather all the text files that correlate to each speed value and move them to Successive Simulation Procedure (SSP).

Successive Simulation Procedure (SSP) works by creating a general directory titled “SignTruss\_KDOT.” This general directory contains four directories: “filtered-input-files,” “signtruss-input-files,” “Staad-anl-files,” and “staad-anl-filtered-files.”

These directories are used based on the SSP’s steps below to run STAAD.Pro files and extract stresses.

- a. Create directory under SProStaad titled as “SignTruss\_KDOT.”
- b. Create four directories under “SignTruss\_KDOT” for input and output files.
- c. Sort STAAD original files in directory “signtruss-input-files” with Macro program “Book1.xlsm.”

- d. Run Macro program “Book1.xlsm” to filter input STAAD original files and save the filtered one as “.txt” in different directory “filtered-input-files.”
  - e. In the “filtered-input-files” three different batch files.
  - f. Run batch file “change-exte.bat” to change filtered input file extension from “.txt” to “.std”
  - g. Run batch file “Cityname-Run-std-files.bat” to run STAAD filtered input files and generate output files “.ANL.”
6. The SSP helps to generate two directories, “signtruss-input-files” and “signtruss-input-files.” These two directories are utilized in FLSS to calculate fatigue life results.
  7. Run FLSS again by inputting the same information that were inputted initially such as desired city, built year, and number of years in service, and run the software. A message will appear again asking if users would like to proceed or stop. Choose “Yes” to allow the software to continue and find the results.

## Chapter 5: Fatigue Life Simulator Software (FLSS)

According to the author's knowledge, Fatigue Life Simulator Software (FLSS) is the first software capable of predicting finite remaining fatigue life of aluminum highway signs, luminaires, and traffic signals. FLSS is an automated programming software that can perform analysis automatically and predict structural fatigue life. The software is completely compatible with STAAD.Pro software to determine the fatigue life of structure members. FLSS is comprised of combinations of several code scripts, and each piece of code script was created individually and tested separately to ensure full functionality. Visual Basic Application (VBA) in Excel is primarily utilized to create all the code scripts and combine them to make FLSS. VBA is user-friendly and offers tremendous flexibility in coding, which makes it ideal for creating FLSS.

Some of the code scripts were written to overcome complications encountered when using KDOT's Sign Truss Interface and STAAD.Pro software. Because Sign Truss Interface is a closed box with no extra features for performing extra analyses, it is only made for limited data entry. The wind velocity mph must be entered manually one value at a time every time the simulated structure is generated to calculate fatigue life, an inefficient process when utilizing 45 years' worth of data. However, the only way to access STAAD.Pro software and generate the desired simulated model is via KDOT's Sign Truss Interface. The software and interface are synchronized together, so when the data are entered and the interface runs, models are generated through STAAD.Pro Software. As it can be seen from Figures 3.5, 3.6, and 3.7, only one slot for velocity value can be entered. Therefore, an automated procedure in Successive Simulation Procedure (SSP) was created to facilitate use of Sign Truss Interface to simulate the wind pressure data associated with each wind velocity. Simulated wind pressure data were fed into the STAAD.Pro software to generate hundreds of successive simulations. STAAD.Pro calculates stresses for the structure's members at every speed value that simulate the wind pressure through Sign Truss Interface. At each time one speed value is input into the Sign Truss Interface, the interface simulates wind pressures of the structural model to generate stresses. Holistically, all speed values of 45 years for high, medium, and low speeds are fed automatically through FLSS to sign truss interface to simulate wind pressures and generate stresses via STAAD.Pro software.

SSP creates a general directory “SignTruss\_KDOT” that contains four directories: “filtered-input-files,” “signtruss-input-files,” “Staad-anl-files,” and “staad-anl-filtered-files.” Use of these directories is based on the following SSP’s steps to run STAAD.Pro files and extract stresses.

1. Create directory under SProStaad named “SignTruss\_KDOT.”
2. Create four directories under “SignTruss\_KDOT” for input and output files.
3. Sort STAAD original files in directory “signtruss-input-files” with Macro program “Book1.xlsm”
4. Run Macro program “Book1.xlsm” to filter input STAAD original files and save the filtered one as “.txt” in different directory “filtered-input-files.”
5. In the “filtered-input-files” three different batch files.
6. Run batch file “change-exte.bat” to change filtered input file extension from “.txt” to “.std”
7. Run batch file “Cityname-Run-std-files.bat” to run STAAD filtered input files and generate output files “.ANL”
8. Run batch “move-ANL.bat” to move output files from the existing directory to “Staad-anl-files” directory.
9. Run batch file “change-exte-output.bat” to change original output “.ANL” file extension from “.ANL” to “.txt”
10. Run Macro program “Filter-ANL.xlsm” to filter input STAAD original output “.ANL” file and save the filtered one as “.xls” in the same directory.
11. Run batch “move-xls.bat” to move filtered output “.xls” files from the existing directory to “Staad-anl-filtered-files” directory.

STAAD.Pro text files, which contain all the simulated structure information, were sorted in “signtruss-input-files” directory with a macro file called “Book1.xlsm.” Once the text files get sorted in the directory, “Book1.xlsm” is ran to filter text files and save the filtered ones as “.txt” in different directory, “filtered-input-files.” The “filtered-input-files” directory has three different batch files: “change-exte.bat,” “Cityname-Run-std-files.bat,” and “move-ANL.bat.” The first batch file “change-exte.bat” changes the extension files in the directory “filtered-input-files” from

“.txt” to “.std.” The second type of batch file is “Cityname-run-std-files.bat,” and there are eight similar batch files, one for every city. These batch files help to generate output files “.ANL.” The other batch files “move-ANL.bat” moves output files from “filtered-input-files” directory to a new directory “Staad-anl-files.” The last batch files “change-exte-output.bat” change original output “.ANL” file extension from “.ANL” to “.txt.” Macro file “Filter-ANL.xlsm.” is run to change original output “.ANL” files and save the filtered one as “.xls” in the same directory. Lastly, batch “move-xls.bat” move filtered output “.xls” files from the existing directory to “Staad-anl-filtered-files” directory as Excel files. The resulting Excel files contained stresses and nodes corresponding to each member. SSP allows users to produce two directories that FLSS software relies on, which are “staad-anl-filtered-files” directory and “signtruss-input-files.”

The directory “staad-anl-filtered-files” contains raw data extracted from the STAAD.Pro software. The data in these files represent load case 1 and load case 2 including files containing data such as member numbers of the structure model, stresses resulted from each wind speed effect (i.e., wind speed blows on members and wind speed blows on sign truss), and fatigue stresses that are resulted from the load combinations of the wind speeds mentioned previously. However, these Excel files are missing nodes that correlated to each member, which is why “signtruss-input-files” directory has been used for FLSS software to extract the nodes from the text files in the directory and insert them into the Excel files that are in “staad-anl-filtered-files” directory. Furthermore, “signtruss-input-files” directory contains all the text files that have extracted data from STAAD.Pro software. STAAD.Pro software is not quite flexible when it comes to the data output, and therefore, it has only this option, which extracts the necessary nodes in the form of text files. Not only nodes are extracted as output, but also several other data are extracted with it, such as joint coordinates, member incidences which have members and their correlated nodes separated by semicolons, member releases, member offsets, member properties, member loads, which consist of member loads on sign truss, and members and load combinations. Sign Truss Interface and STAAD.Pro software do not have various features of extracting stresses and nodes in different file format, so FLSS significantly modified this feature.

The first code script (subroutine getStresses) was made for “staad-anl-filtered-files” directory, particularly for extracted Excel files. The code first opens the directory and by using the

file names, looping over all the Excel files to create a sheet called “Results.” Once the “Results” sheet is created in the first Excel file, the code extracts all member numbers and their corresponding axial stresses from the “main sheet” and inserts them into the “Results” sheet. This process is repeated until no Excel files remain in the directory. The code works as follows, from the main sheet it reads the member numbers first and then it finds their corresponding axial stresses and divides them by 1,000. The reason the axial stresses are divided by 1,000 is to convert them from psi to ksi since the stresses are extracted in psi from STAAD.Pro. Since there are several types of load combinations (LC 17, LC 18, and LC 19), the code loops over the structure’s member numbers and takes their corresponding axial stress at load combination 19. The same process is applied to all member numbers and their axial stresses and then all are saved in “Results” sheet with their corresponding member numbers. In other words, “Results” sheets have all the member numbers and their corresponding stresses measured by ksi.

The second code script (function readTextFile) was made for “signtruss-input-files” directory, particularly for the extracted text files that contain the nodes. The code initially opens the directory and loops over all text files, reading them one by one. A dictionary is then made to extract member numbers and their corresponding nodes; each text file is named “1” for easy accessibility. As mentioned previously, the text files have several types of data which are unnecessary for this process, and the text files are case sensitive due to the fact that all text files that have data at the same row end with either a semicolon or a space. For this reason, several “if (condition)” statements were made within the code loop had to be made. The first “if (condition)” statement avoids all the other data and extracts only member numbers and their corresponding nodes. The line of code starts by the word “Read” to be able to read all the rows and extract only the data that are between “Member Incidences” and “Member Release” (i.e., data are member numbers and their corresponding nodes). The second “if (condition)” statement saves member numbers and their corresponding nodes in an individual dictionary. The member numbers are saved as key directory and nodes are saved as items dictionary; data in VBA/directory can be saved in a form of key which is the main component and items that are their correspondences. This function is made to be called out anytime it’s needed. Therefore, this function has been called at the first code script (subroutine getStresses) to insert the nodes at the main sheet of the Excel files,



after creating two columns named “Node 1” for the first column and “Node 2” for the second column.

The third code script (subroutine LoopFiles) contains its own syntax lines in addition to numerous function codes to be called for every time are needed. The subroutine’s code syntax is structured to extract stresses that resulted from the effect of the wind speed that the structure is subjected to at each city. This code focus is on the “staad-anl-filtered-files” directory and its Excel files after the “Results” sheet is created, and all member numbers and their corresponding stresses are saved there. The subroutine tasks extract all the stresses resulted from all selected speed values at each member, using the values in the “Results” sheet. Then at each stress range level, divide the summation of the repeated speeds by the corresponding N-Cycles of the highest stress value at each stress range. The result of dividing the repeated speeds by the corresponding N-Cycle of the highest stress value at each stress range level is fatigue life ratio. Summing up all the fatigue life ratios for all the stress range levels results in finding fatigue life for a specific member.

The subroutine LoopFiles has multiple functions which each perform a specific task. For example, the function “SheetExists” was used in the first code script to check if the sheet “Results” exists or not, and the second one is the results Excel that has all member numbers and their corresponding fatigue life results. The “SheetExists” function reads every sheet name and the workbook is assigned as optional, so if the workbook is not specified then use the existing sheet, otherwise, use the current active sheet. Another function that gets called out is the onlyDigits. This function is extremely important since the code is automated. This function reads file names and extracts only the digits, which are the speed values. The reason for that is to use the speed values as a range to loop over each member and extract stresses that are exerted in the “Results” sheet due to each speed effect. Function “loopOverKSI” is one of the most important functions due to its priority of dealing with current sheet per city, repeated speeds, stresses, and N-Cycles. The repeated speeds are read and saved by another function script (getRepeatedSpeeds) which will be mentioned later in this section. The N-Cycles is determined in another function (getNCycles) which will also be mentioned later in this chapter. Through this code, the fatigue life of each member gets determined. The summation of the repeated speeds of each stress range is divided by the N-Cycles of the corresponding highest stress values at each range. Through this code and by

using an “if” statement for the fatigue life of each member, it is distinguished if the result implemented. The fatigue life of a member is distinguished by color codes in order to identify their priorities.

The “LoopOverKSI” function helps to determine the fatigue life ratio at each stress range level and identify the color codes by using the “Interior.ColorIndex” built-in function. The function “getAllMembers” is also important because it is responsible for extracting the member numbers of the structural model from the “Results” sheet and saving them in a dictionary (mems) as keys (memKey). The dictionary (mems) feeds the member numbers to the result sheet that has the member numbers and their corresponding fatigue lives; the results sheet works in the background and is not displayed yet. These member numbers will be used as a loop to go over all members and determine their fatigue lives by including stresses, N-Cycles, and repeated speeds. The reason for doing that is due to the variation of structural models, so each structural model has specific numbers elements. Some structural members are larger with many member elements and others with less member elements, so this function takes the number of member elements and creates a loop. There is a function called (SortDictionary) which helps to sort the member numbers in the dictionary because at the time of extraction they were unsorted. “Application.Small” is a built-in function to sort the member numbers from small to larger in order.

Another subroutine called “generateRepeatedSpeeds” is responsible for calculating the repeated speeds from the 45 years’ worth of data. The subroutine relies on the speed.xlsm file that is located in the “NCyclesAndRepeatedSpeeds” directory because that is where the speed values are saved. The file contains all the 45 years’ worth of data and the calculation of repeated speeds and their corresponding speed value are displayed there. Once users make their selections (city name, year built, and number of years in service), the subroutine loops over the 45 years of wind speed data starting from the built year and loops over all the years in service minus 1. For instance, if the built year was 1983 and the number of years in service was for 23 years, then the code will loop from 1983 to 2005. Accordingly, the repeated speeds will be calculated within this range. The repeated speeds are calculated based on the daily wind fluctuation, so they are calculated per seconds by multiplying high-speed by 21,600, medium-speed by 43,200, and low-speed by 21,600. The repeated speeds of each speed type are combined for one total repeated speed that correspond

to a certain speed value. Repeated speeds have their own function called “getRepeatedSpeeds.” This function reads repeated speed values from the text files stored in the “NCyclesAndRepeatedSpeeds” directory and uses them to determine fatigue lives. These repeated speeds change based on the users’ selections of year built and years in service. Every time users change their inputs, these repeated speeds are changed and accordingly the fatigue life values are changed. Each of the eight cities has its own repeated speeds text file and the repeated speeds change based on the selected city.

Two more functions were used in determining the right N-Cycle value: “findValue” and “getNCycles.” The two functions depend on data of S-N curve in ncycles.xlsx, which is located in the NCyclesAndRepeatedSpeeds directory. The “findValue” function helps to match the stress values from the structure to the ones in the ncycles.xlsx file and once it finds a larger value, then an interpolation process is performed to find a corresponding N-Cycle value for the stress value from the structure. Then, an “if” statement is used to find for each stress value from the structure its corresponding N-Cycle value and store them in an array. The array consists of six indexes; each index is for a ksi range. After finding the proper N-Cycle value at ksi range level, the function “getNCycles” is called out at subroutine “LoopOver” to be used with repeated speeds and find fatigue life.

The subroutine “UserForm\_Initialize” links the necessary information to the three drop-down buttons. The built-in function, Me.ComboBox1.AddItem “cityName,” is used to create the first drop-down button where all the eight cities are displayed. ComboBox2 and ComboBox3 were made under a loop for 45 years from 1975 to 2019. All three ComboBoxes are linked to the “ListIndex” built-in function and an “if (condition)” statement at the beginning of the code syntax. The “if” statement helps the software to be more user-friendly. Consequently, if there is no selection, a message box displays a warning which will remind the user to properly make selection. If users make the right selections, then the code proceeds to calculate fatigue lives.

## Chapter 6: Probabilistic Verification of the Deterministic Model

This study utilized the probabilistic approach to determine if the  $\frac{1}{4}$ -day recurring model was applicable and valid statistically for analyzing the existing 45 years' worth of wind data. Thus, the probabilistic approach took into consideration 45 years' worth of data for each of the eight cities used in the deterministic approach. The wind speed cycles were counted at every season for each speed type and then combined, unlike in the deterministic approach where the speed repetitions were counted for the entire 45 years at every speed type and then combined. The speed types refer to high, medium, and low speeds; the speed values indicate the number of speed mph; and the speed cycles/repetitions are the repeated speeds that correspond to each speed value. The probabilistic approach divided the years into seasons by individually accounting for each season for the entire 45-year period. For example, winter season's data were separated from the other seasons and gathered for 45 years since all seasons represent an entire year worth of data. When determining a speed value for instance, the speed cycles of that speed value were counted for the winter season only for the 45 years. In other words, the speed cycles of speed value number 4 for example, was counted during winter season only as a low speed. Speed value number 15 for example was counted as a medium speed, and so for 45 years during the winter season only. The same methodology was applied for all the speed values depending on the speed range because the speed range determines speed type.

This probabilistic approach proposes splitting speed values of speed types (high, medium, and low) into ranges, but speed values cannot be duplicated among ranges. In other words, if a speed value was calculated for a speed range of a speed type, then this speed value should not be used again in any other range. Furthermore, the scope of each range could vary from season to season causing speed values to shift to a different speed type. For example, if speed value 4 mph was determined to be in a low speed during winter season, then this speed value would be low speed throughout the calculation of the winter season. However, speed value 4 mph may shift to medium speed in a different season. Low speed in the winter season has a range of 1–8 mph, while medium speed's range is 9–25 mph, and high-speed range is 26–56 mph. After separating the data into seasons, a code script was written to calculate the speed cycles for every speed value during

a specific season for the entire 45 years. This process was performed at each of the eight cities: Manhattan, Hill City, Wichita, Dodge City, Topeka, Garden City, Chanute, and Goodland.

For example, for the city of Manhattan, after the seasons were categorized as winter, spring, summer, or fall, then speed types were identified as high, medium, or low speeds for each season. Table 6.1 shows speed ranges identified at each speed type; speed values and speed cycles are listed below them. Code script calculated speed cycles for every speed value that was not zero or had zero speed repetition, and it calculated speed cycles and counted their speed values as speed index in a matrix. Then, the code quantified the number of speed indexes, such as 33 speed indexes Manhattan during the winter season, and multiplied those indexes by the proportion percentages (0.25, 0.5, and 0.25) of the  $\frac{1}{4}$  day recurring model. Multiplying the 33 speed indexes by 0.25, the weight of low speed during the day, resulted in eight speed indexes after rounding qualifying it in the range of low speed (1–8), as shown in Table 6.1. Once the speed value within the first season was specified, then the speed repetitions of each speed value of low speed range were calculated. The same procedure was applied for medium speed type by identifying the speed range (i.e., 33 speed indexes was multiplied by 0.5), which is the weight of medium speed during the day. This resulted in 17 speed indexes that represent the scope of range of medium speed. The speed cycles of each speed type were calculated, as shown in Table 6.1, and the scope range of high speed was identified by considering the remaining of the speed indexes into the calculation. For example, speed value 4 mph was counted as a low speed according to the range of low speed, so 266 was the number of speed cycles during the winter season, as shown in Table 6.1. In the spring season, speed value 4 mph was repeated 241 times, while in summer and fall seasons it was repeated 151 and 151 times respectively. As indicated in the table, speed ranges vary from speed to speed and from season to season.

**Table 6.1: Manhattan Speed Values and Corresponding Repeated Speeds Per Season**

Winter			Spring			Summer			Fall						
range	High	Avg	Low	range	High	Avg	Low	range	High	Avg	Low	range	High	Avg	Low
	26--58	9--25	1--8		29--67	10--28	1--9		24--40	8--23	1--7		24--58	8--23	1--7
Speed	Speed Repetition		Speed	Speed Repetition		Speed	Speed Repetition		Speed	Speed Repetition		Speed	Speed Repetition		
1			145			135			195						105
2			315			120			225						350
3			187			197			292						162
4			266			241			151						151
5			160			265			165						165
6			111			101			76						106
7			100			210			150						75
8			85			120			415					425	
9		386				75			231					196	
10		175				385			270					250	
11		236				226			256					211	
12		191				206			106					181	
13		150				245			120					210	
14		105				225			90					90	
15		105				90			75					125	
16		85				75			15					50	
17		30				105			15					75	
18		30				120								15	
19		26				76			1					16	
20						15									
21		15				30									
23						25									
24													170		
25									30				75		
26	75								10				45		
27															
28	56								1				16		
29	40					135			15				20		
30	15					75							15		
31						15			15						
32						30							30		
33	15					25									
34	15					15			15						
36						15									
38	15														
40									15						
58	15												15		
60						15									
63						15									
67						15									

All calculated speed cycles were summed as the total number of speed cycles for every speed type during each season, as indicated in Table 6.2. As shown, the total number of speed cycles during winter for high, medium, and low speeds were 246, 1,534, and 1,359, respectively. The same procedure was applied to the rest of the seasons, and then all high-speed values were summed from all seasons, resulting in one total high-speed number throughout the 45 years (i.e., 1,088 cycles). Summations of medium and low speeds throughout the 45 years were 6,795 cycles and 5,201 cycles, respectively. Summation results of each speed type in Table 6.2 were summed for a total number of speed cycles throughout the 45 years (i.e., 13,084 cycles). Each speed type's total number of speed cycles was divided by the total number of speed cycles throughout the 45

years resulting in observed values of high, medium, and low speeds (i.e., 0.083, 0.5193, and 0.397), respectively. This calculation identified probabilistic propositional percentages and compared them to expected percentages of the ¼-day recurring model to validate their significant difference. If the difference was significant then no correlation existed between the deterministic approach and the probabilistic approach, and if the difference was minimal, then the two models were correlated and more likely to be acceptable. The percentages of the probabilistic model are called the Observed Values (O), and the ¼-day recurring model percentages are called the Expected Values (E). Moreover, Table 6.2 shows Chi-square statistic and its P-value (probability percentage value, also known as Chi-Square test).

**Table 6.2: Manhattan Repeated Speed Summation per Season, Chi-Square Value and P-Value**

	winter			Spring			Summer			Fall		
	High	Avg	Low	High	Avg	Low	High	Avg	Low	High	Avg	Low
Speed repetition	246	1534	1369	355	1823	1464	101	1594	1254	386	1844	1114
			<b>Observed</b>	<b>Expected</b>								
speeds for 45 years			Percentage									
High=	1088		8.32E-02	0.25		<b>chi-square</b>						
Avg=	6795		5.19E-01	0.5		1.99E-01						
Low=	5201		3.98E-01	0.25		<b>P-Value</b>						
						9.05E-01						
Total=	13084											

Chi-Square Statistic is a statistical method that assesses the goodness of fit and measures the significant difference between observed values and those expected theoretically. The equation for the chi-square statistic is:

$$\chi_c^2 = \sum \frac{(O_i - E_i)^2}{E_i}$$

Subscript “c” refers to the number of degrees of freedoms (degree of freedom = number of categorical variables - 1). “E” is the expected value or actual value used in the ¼-day recurring model (i.e., 0.25, 0.5, and 0.25 for high, medium, and low speeds, respectively). “O” is the observed value, which is what the probabilistic approach is proposing to use as compatible values to the 0.25, 0.5, and 0.25. The summation symbol means that a calculation must be performed for every single data item between the observed and expected values. Chi-square statistic is one way to show a relationship between numerical (countable) variables and non-numerical (categorical)

variables. The Chi-square statistic is a single number that tells how much difference exists between observed counts and expected counts, or that no relationship exists in the population. A low value for Chi-square means a high correlation between two sets of data. In theory, if the observed and expected values are equal (no difference) then Chi-Square would be zero, an event that is unlikely to happen in life. Chi-square value is calculated using the Chi-square formula:

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i}$$

This value is then compared to a critical value from a Chi-square table; see Table 6.3 below.

A Chi-Square test provides P-value (probability value), which is the result of testing the Chi-square statistic to determine if the result is significant. The higher the magnitude of P-value the more accurate the model is. This is another method to check and verify results beside Chi-square statistic. In order to test Chi-square and find P-value, two steps must be followed:

1. Determine the number of degrees for high, medium, and low speeds. The degrees of freedom can be calculated using Chi-square degree of freedom ( $df = n - 1$ ), where  $n$  is the speed type.
2. Alpha level ( $\alpha$ ) is chosen by the researcher, so 0.05 is the value chosen just like the area value chosen to determine Chi-Square's critical value from Table 6.3.

There are two ways to calculate P-value. One way is by a built-in function in Excel spreadsheet, which is CHITEST= (sum of the observed values, sum of the expected values).

The second way is by few steps:

1. Subtract each observed value individually from their corresponding expected value.
2. Square the results of each corresponding value.
3. Divide the squared values by the corresponding expected values.
4. Sum up all values to obtain P-value. Once the P-value is calculated for each city, it is compared to the alpha ( $\alpha$ ) value from Chi-square table, and according to the P-value's magnitude, the level of acceptance can be determined.



The alpha value ( $\alpha$ ) chosen from Table 6.3 is 0.05 (5% engineering judgment), with only two degrees of freedom, resulting in a critical value of Chi-square equal to 5.991. If the calculated Chi-Square value is more than the critical value, then a significant difference is evident, and the ¼-day recurring model is inaccurate. If the Chi-square value is smaller than the critical value from the table, then the model is more likely to be accurate. Similarly, the smaller the calculated Chi-square value from the critical value, the more likely the model is accurate, and no significant difference is evident. For example, the calculated Chi-square measure (e.g., 0.19) for Manhattan was determined to be significantly lower than the critical value for  $\alpha = 0.05$  with two degrees of freedom (5.991). Similarly, the p-value for  $\alpha = 0.05$  was found to be much higher than the 0.05 (e.g., 0.90), indicating no significant difference between the observed and expected values. Thereby proving the accuracy of the deterministic approach. The calculations and comparisons were conducted for all eight cities, and their values are listed in Tables 6.4 through 6.11. Results showed that all the observed versus expected values at each city were proportional and close in magnitude, which was a reasonable verification to validate the ¼-day recurring model. In Manhattan, for example, the P-value was 0.90, meaning 90% the model was acceptable in comparison to 5% alpha value (i.e., percent of rejection). Table 6.12 represents the P-values of the eight cities and their comparison to the selected alpha value, so Table 6.12 indicates that the highest P-value was in Topeka, which is 93% acceptance to the model. The lowest P-Value was at Garden city, which was 85% acceptance to the model. These values highlighted the goodness of fit of the expected values to the observed values, and the significant difference between the two sets of data was minimal. This result proved the correlation of ¼-day recurring model (0.25, 0.5, and 0.25) to the observed values that were calculated through the probabilistic approach (0.083154998, 0.519336594, and 0.397508407).

**Table 6.3: Chi-Square Critical Value Table**

Alpha \ DOF	0.995	0.99	0.975	0.95	0.9	0.75	0.5	0.25	0.1	0.05
1	4.00E-05	1.60E-04	9.80E-04	3.93E-03	1.58E-02	1.02E-01	4.55E-01	1.32E+00	2.71E+00	3.84E+00
2	1.00E-02	2.01E-02	5.06E-02	1.03E-01	2.11E-01	5.75E-01	1.39E+00	2.77E+00	4.61E+00	5.99E+00
3	7.17E-02	1.15E-01	2.16E-01	3.52E-01	5.84E-01	1.21E+00	2.37E+00	4.11E+00	6.25E+00	7.81E+00
4	2.07E-01	2.97E-01	4.84E-01	7.11E-01	1.06E+00	1.92E+00	3.36E+00	5.39E+00	7.78E+00	9.49E+00
5	4.12E-01	5.54E-01	8.31E-01	1.15E+00	1.61E+00	2.67E+00	4.35E+00	6.63E+00	9.24E+00	1.11E+01
6	6.76E-01	8.72E-01	1.24E+00	1.64E+00	2.20E+00	3.45E+00	5.35E+00	7.84E+00	1.06E+01	1.26E+01

**Table 6.4: Manhattan Observed and Expected Values for High, Medium, and Low Speeds**

City:	Expected ( E )	Observed (O)
Manhattan		
High	0.25	8.32E-02
Average	0.5	5.19E-01
Low	0.25	3.98E-01

**Table 6.5: Hill City Observed and Expected Values for High, Medium, and Low Speeds**

City: Hill	Expected ( E )	Observed (O)
City		
High	0.25	8.32E-02
Average	0.5	5.19E-01
Low	0.25	3.98E-01

**Table 6.6: Wichita Observed, Expected Values for High, Medium, and Low Speeds**

City: Wichita	Expected ( E )	Observed (O)
High	0.25	8.32E-02
Average	0.5	5.19E-01
Low	0.25	3.98E-01

**Table 6.7: Dodge City Observed and Expected Values for High, Medium, and Low Speeds**

City: Dodge	Expected ( E )	Observed (O)
City		
High	0.25	8.32E-02
Average	0.5	5.19E-01
Low	0.25	3.98E-01

**Table 6.8: Topeka Observed and Expected Values for High, Medium, and Low Speeds**

City:	Expected ( E )	Observed (O)
Topeka		
High	0.25	8.32E-02
Average	0.5	5.19E-01
Low	0.25	3.98E-01

**Table 6.9: Garden City Observed and Expected Values for High, Medium, and Low Speeds**

City: Garden	Expected ( E )	Observed (O)
City		
High	0.25	8.32E-02
Average	0.5	5.19E-01
Low	0.25	3.98E-01

**Table 6.10: Chanute Observed and Expected Values for High, Medium, and Low Speeds**

City:	Expected ( E )	Observed (O)
Chanute		
High	0.25	8.32E-02
Average	0.5	5.19E-01
Low	0.25	3.98E-01

**Table 6.11: Goodland Observed and Expected Values for High, Medium, and Low Speeds**

City:	Expected ( E )	Observed (O)
Goodland		
High	0.25	8.32E-02
Average	0.5	5.19E-01
Low	0.25	3.98E-01

**Table 6.12: Eight Cities in Kansas and Their Corresponding P-Values**

Alpha = 0.05	
City	P-Value
Manhattan	9.05E-01
Hill City	8.93E-01
Wichita	8.90E-01
Dodge City	9.08E-01
Topeka	9.36E-01
Garden City	8.59E-01
Chanute	8.97E-01
Goodland	8.65E-01

Chi-square and P-value verifications were used at every season for each city to further demonstrate the correlation accuracy between the ¼-day recurring model set of data and the probabilistic approach set of data; Chi-square and P-value verifications were used at every season for each city. For example, Chi-square was calculated for winter season to be 0.2550189 for Manhattan, a value that was much less than the Chi-square critical value (5.991) from Chi-square table. Chi-square values from the other seasons were also calculated, so spring was 0.1854454, summer was 0.3122989, and fall was 0.1053719. P-value of each season was also calculated, so winter was 0.8802851, spring was 0.9114462, summer was 0.8554313, and fall was 0.9486779. The P-value of winter season was 88% acceptance to the model. Fall season's P-value was 94%, indicating extreme acceptance to the model and showing the significant difference was minimal. Table 6.13 lists Chi-square and P-values of all cities to allow easy review and identify the level of acceptance to the ¼ day recurring model.

**Table 6.13: Chi-Square and P-Value per Season in Eight Kansas Cities**

<b>Manhattan</b>	winter	Chi-square	2.55E-01		<b>Topeka</b>	winter	Chi-square	1.30E-01
		P-value	8.80E-01				P-value	9.37E-01
	Spring	Chi-square	1.85E-01			Spring	Chi-square	1.33E-01
		P-value	9.11E-01				P-value	9.35E-01
	Summer	Chi-square	3.12E-01			Summer	Chi-square	1.31E-01
		P-value	8.55E-01				P-value	9.37E-01
	Fall	Chi-square	1.05E-01			Fall	Chi-square	1.33E-01
		P-value	9.49E-01				P-value	9.35E-01
<b>Hill City</b>	winter	Chi-square	2.91E-01		<b>Garden City</b>	winter	Chi-square	4.01E-01
		P-value	8.64E-01				P-value	8.18E-01
	Spring	Chi-square	1.25E-01			Spring	Chi-square	1.89E-01
		P-value	9.39E-01				P-value	9.10E-01
	Summer	Chi-square	3.85E-01			Summer	Chi-square	3.49E-01
		P-value	8.25E-01				P-value	8.40E-01
	Fall	Chi-square	1.79E-01			Fall	Chi-square	3.24E-01
		P-value	9.14E-01				P-value	8.50E-01
<b>Wichita</b>	winter	Chi-square	2.19E-01		<b>Chanute</b>	winter	Chi-square	1.19E-01
		P-value	8.96E-01				P-value	9.42E-01
	Spring	Chi-square	2.06E-01			Spring	Chi-square	3.50E-01
		P-value	9.02E-01				P-value	8.40E-01
	Summer	Chi-square	3.20E-01			Summer	Chi-square	1.45E-01
		P-value	8.52E-01				P-value	9.30E-01
	Fall	Chi-square	2.03E-01			Fall	Chi-square	3.67E-01
		P-value	9.03E-01				P-value	8.33E-01
<b>Dodge City</b>	winter	Chi-square	2.65E-01		<b>Goodland</b>	winter	Chi-square	3.94E-01
		P-value	8.76E-01				P-value	8.21E-01
	Spring	Chi-square	1.42E-01			Spring	Chi-square	1.67E-01
		P-value	9.31E-01				P-value	9.20E-01
	Summer	Chi-square	2.78E-01			Summer	Chi-square	3.36E-01
		P-value	8.70E-01				P-value	8.45E-01
	Fall	Chi-square	1.29E-01			Fall	Chi-square	3.23E-01
		P-value	9.37E-01				P-value	8.51E-01

# Chapter 7: Conclusion and Recommendations

## 7.1 Conclusion

The Kansas Highway System currently utilizes over 450 sign truss structures, most of which are 30–45 years old. Although a majority of the sign truss structures are comprised of welded aluminum connections with potentially fatigue prone details, these structures have not had fatigue evaluations to determine remaining fatigue life throughout their service time span. Therefore, this study was initiated to investigate the possibility of estimating the remaining fatigue life for each aluminum element according to AASHTO LRFD wind load combinations. Consequently, Fatigue Life Simulator Software (FLSS) was developed to work compatibly with STAAD.Pro software and Sign Truss Interface to determine fatigue life results for any model of structural support system in the state of Kansas.

FLSS can predict the remaining fatigue life of all structural elements by counting the years since a structure was built and the years in service. Users must follow the deterministic approach procedure illustrated in Figure 5.1 to generate results. This research made fatigue life predictions of three representative models for evaluation and comparison purposes. Two models were provided by KDOT and one model was built by the investigators to increase comprehensive perspective. Each model was subjected to the 45-year wind speed data of the eight cities selected to represent the state of Kansas. The following significant findings were compiled by analyzing the three models subjected to the 45-year wind speed data for the eight cities.

1. All three support structural models had natural frequencies that were significantly higher than the 1.0 Hz frequency of the exciting wind cycles. More specifically, Model 1 had 30.28 Hz, Model 2 had 21.98 Hz, and Model 3 had 32.48 Hz as their fundamental natural frequencies. Therefore, static analysis is valid since the dynamic amplification factor may be assumed equal to 1.0.
2. Support structures in Garden City, Dodge City, and Goodland demonstrated nearly spent fatigue life under the effect of 45 years' worth of wind at the primary members attached to the foundation of the three support structures. Other cities in Kansas have shown less used-up fatigue life in these same

members (i.e., 0.9–0.96 Miner rule ratio) under the effect of 45 years' worth of wind.

3. When the service life span for the examined models was less than 45 years (e.g., 30 years) the spent fatigue life is much lower (i.e., around 0.68 Miner's rule ratio for critical members in Garden City).
4. FLSS software estimates remaining fatigue life for any non-cantilevered highway sign truss members with any specified year of construction after 1975 up to 2019. KDOT evaluators are expected to examine representative models in various locations around the state to make informed decisions.
5. The present probabilistic analysis showed the current deterministic model to be valid and accurate according the Chi Square evaluation and the probability of significant difference (P-value).

FLSS works compatibly with STAAD.Pro software and Sign Truss Interface to analyze any selected simulated structural model to estimate the amount of deterioration during years of service and determine remaining fatigue life span. Sign Truss Interface simulates wind pressure to generate stresses through wind effects acting on STAAD.Pro software. Sign Truss Interface works as a closed box because its code scripts were locked with no allowed access to the code scripts to automate its functionality with FLSS. In addition, the interface has only one field in which wind speeds (mph) could be input manually. Because of the manual input feature, a challenge was encountered to feed the 45 years' worth of wind speeds data automatically to the interface and simulate them into wind pressure, and then calculate eventually the corresponding stresses. Therefore, a modification was made to the output files of the interface to incorporate AASHTO load case 1 and 2 into the output files, so the stresses could be calculated based on the load cases. Consequently, the 45 years' worth of data could be fed automatically into the interface before simulating hundreds of structural models, and then those output files could be used in FLSS to calculate fatigue life. FLSS is the first software to analyze and estimate remaining life spans of overhead aluminum welded structures throughout their service lives.

## 7.2 Future Research

More research should be conducted on other components of the structures, such as mast arm connection in the case of cantilevered traffic signal. It is important to study and understand the behaviors of these components under the effects of the wind speed fluctuation. Additionally, a more urgent investigation is warranted for the more critical cantilevered and butterfly type support structures to avoid their sudden and unexpected collapse in service.

The following recommendations are summarized below for future research:

1. KDOT evaluators are advised to run the FLSS for representative support structure models subjected to the actual number of years in service throughout Kansas.
2. Results of spent fatigue life approaching the value of 1 must prompt evaluators to look for fatigue cracking in critical members and adjoining connections if the Miner's rule ratio for such members exceeds 0.95.
3. The wind database be extended for the next 10 years to extrapolate the fatigue life of critical members for extended life spans.
4. Repair or replacement of members and adjoining connections should reset the service life span of members by running the FLSS program using the replacement year as the starting year for these replaced elements.
5. An urgent investigation is warranted for critical cantilevered and butterfly type support structures to avoid their sudden and unexpected collapse in service.
6. More research should be conducted on structural components such as mast arm connections in cantilevered traffic signals. The behaviors of these components under the effects of wind speed fluctuation must be further studied.



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# K-TRAN

## KANSAS TRANSPORTATION RESEARCH AND NEW-DEVELOPMENT PROGRAM

