Structures Research Services 2018-2021

Task 1 Final Report - Overhead Sign Failure Investigation

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16. Abstract

A variety of structural supports exist to mount signs along highways. One type of support is a truss that spans the width of the highway that allows for the placement of overhead signs. These trusses are subject primarily to wind and gravity loads. The connections between the chords and the diagonals are typical fillet welded. Fillet welds are a fatigue prone detail and the welding potentially can leave a heat affected zone which affects the strength of the joints and the members. A truss with severe cracking near Obetz, Ohio was identified by the Ohio Department of Transportation and removed from service.
Research team members inspected the trusses in the field on March 14, 2018 after they were removed from service. The cracking was mapped and elements of the truss including cracked and undamaged joints were removed from the truss and transported to the University of Toledo. Figure 1 shows a cracked horizontal chord member.

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Introduction

Fractures were observed in an overhead sign support truss on Alum Creek Drive at the I-270 interchange near Obetz, OH. The structure is a three-dimensional aluminum space truss having a span of 90’ resting on tubular steel columns. The truss was mounted over steel supports using U-bolts at a height of 23’ from the ground. Four parallel aluminum chords run along a 4’ by 4’ grid to which aluminum diagonals are welded at intervals. The chords of the truss are circular hollow tubes having outer diameters as 5.5” and a 0.25” wall thickness. The horizontal and internal diagonals have a 2” outer diameter with 0.188” wall thickness. The vertical diagonals are 1.9” circular hollow tubes with 0.145” wall thickness. At the time of installation two traffic signs of sizes 12’×7.5’ and 13’×5.5’ were mounted by 3-Z bar assemblies. These signs were later replaced by two smaller signs of size 5’×3’. The exact date of the truss installation is not known, but estimated to be in the late 1960’s to early 1970’s. After the failure was observed and documented, the truss was dismantled from the supports as shown in Figure 1. The dismantled truss was then further documented and cut into numbered sections for further study.

Figure 1: Dismantled truss

Objectives

The primary objectives of this study were:

1. Determine the cause(s) of the failure.
2. Determine the nature and extent of load forces acting upon the truss.
3. Propose to the Ohio Department of Transportation (ODOT) recommendations based upon these findings.

Tasks

To meet these objectives, three tasks were completed as part of this forensic study

1. Material characterization of both the failed region and regions without failures was performed on sections extracted from the failed truss.
2. The wind loading on the truss was studied analytically
3. The thermal loading on the truss was studied analytically.

To facilitate the accomplishment of these tasks, the physical dimensions and specifications of the truss were provided to the University of Toledo (UT) by ODOT in order to perform stress modeling for both thermal and wind induced loading forces. The sectioned pieces of the dismantled truss were also provided to UT for material testing and laboratory failure analysis.

Field Assessment

A team of UT researchers along with ODOT inspectors visited the site of failed truss to examine the failed truss, apparent fracture surfaces, and to identify pieces to be cut out for future study. Circumferential fractures were observed to occur in two different locations within the truss: at one location the aluminum truss chord was completely severed, shown in Figure 2, and a second location where the fracture had not yet advanced through the chord, shown in Figure 3. Both locations were near weld junctions of the diagonals and chord.

Figure 2: Complete fracture observed at one location within the truss

Figure 3: Partial fracture observed at second location within truss

Preliminary visual inspection of the fracture surface revealed two different cross section characteristics: a smaller smooth surface (reflecting instantaneous material failure, likely a region of crack initiation) and a much larger uneven and irregular surface (likely due to a slower material failure, such as fatigue). However, there are several other factors that can exacerbate this failure mode (such as overloading, heat-zone effects, corrosion, weld defects, etc.) requiring more sophisticated laboratory material and failure analysis to be performed at the University of Toledo.

Analytical Modelling

Wind Effects

The goals of the wind analysis were:

1. Develop an analytical model of the truss to compute the response of truss to natural wind gusts.
2. Based on the American Association of State and Highway Transportation Officials (AASHTO) support specifications, compute design load capacity of the truss and check if design is adequate.
3. Identify the elements prone to fatigue failure and evaluate their fatigue life due to natural wind gusts.

Static analysis

As the first step in the investigation, a finite element model of the aluminum truss was developed using the commercially available SAP2000 software package. Equivalent static wind loads calculated in accordance with AASHTO code (LRFD Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals-2015) and dead loads were applied on the truss and a linear elastic static analysis was performed. The results from the analysis were examined to determine the maximum stresses in the truss and to identify the critical members. Based on the location of highly stressed joints and failue locations, select members were identified as critical and are shown in red in Figure 4. Results for these critical members are presented in Table 1. As expected, the maximum stresses were found to occur for larger sign boards and at the end of the truss. The chord member C329 experiences the highest stress, however it is below the allowable stress for welded aluminum.

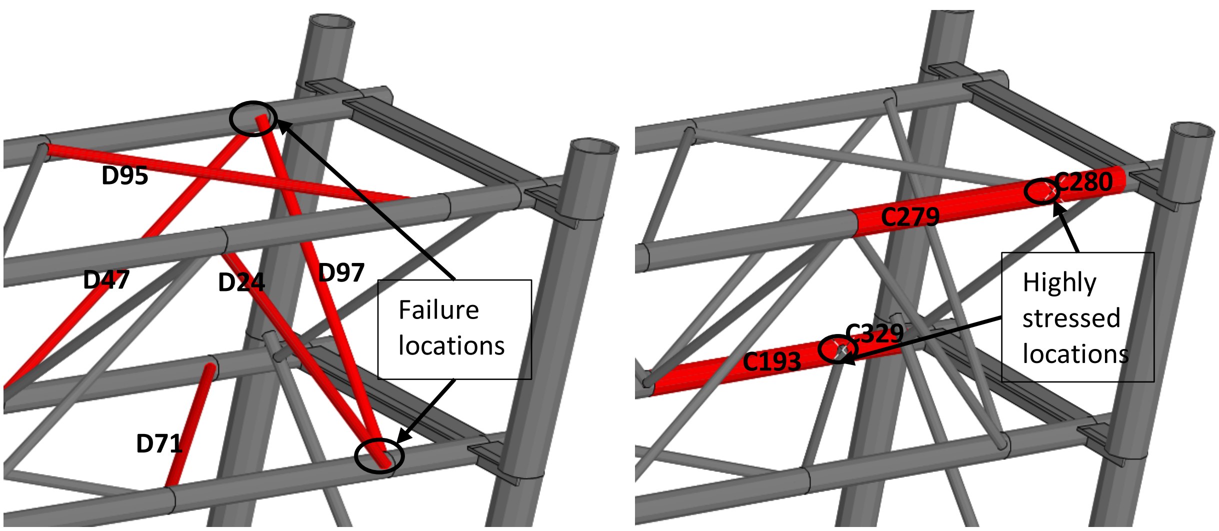


Figure 4: Critical members identified during load simulations

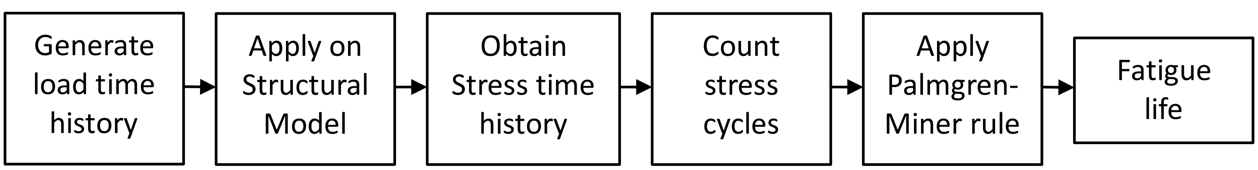
Table 1: Stresses in critical members for design wind and gravity loads

Member	Stress (Small sign) (ksi)	Stress (Large sign) (ksi)	% Reduction
C329	5.3	11.9	55
C193	5.2	11.7	55
C280	4.6	10.5	56
C279	3.9	8.9	56
D71	5.3	11.8	55
D95	4.8	11.0	56
D24	1.7	3.9	56
D47	1.9	4.3	56
D97	1.8	4.1	56

The size of the sign board has a considerable effect on the maximum stresses experienced by the structure. Replacing the older, larger sign boards (sign area = 160 ft^2) with smaller ones (sign area = 30 ft^2) leads to a reduction of around 80% in sign area- reduced the maximum stresses by 55%.

Fatigue Life Evaluation

To accurately assess the fatigue performance of the structure, detailed fatigue life evaluation based on wind load history generated from past wind data was carried out. The methodology used is as described by the flow chart.



To make the analysis computationally inexpensive, a representative time of 60 seconds was selected to develop the transient wind load history and corresponding damage in critical members was calculated. The yearly damage was then found by multiplying the summed damage from 60 second wind load at a specific wind speed by the number of effective 60 second periods/year of the corresponding wind speed. The life expectance of the element, which can be calculated by dividing the total damage by one year and then taking the reciprocal value, is shown in Table . The horizontal diagonal at the top (D95 in figure 4) was found to be most critical with an expected fatigue life of 72 years which exceeds the expected service life of the truss (typically

50 years). In this analysis, the weld details are considered category E' and the corresponding E' allowable stresses for aluminum were used. The procedure for determining the S-N curve for aluminum was adopted from Huckelbridge and Metzger 2009).

Table 2: Yearly damage for various wind speeds and expected life of critical members

Wind speed	Total damage per year				
	Element 24	Element 47	Element 71	Element 95	Element 97
5	7.6E-08	5.5E-08	1.3E-06	1.9E-06	6.8E-08
10	1.5E-05	1.0E-05	2.4E-04	3.7E-04	1.3E-05
15	7.1E-05	5.2E-05	1.2E-03	1.8E-03	6.4E-05
20	1.5E-04	1.1E-04	2.5E-03	3.8E-03	1.4E-04
25	1.9E-04	1.5E-04	3.3E-03	5.1E-03	1.8E-04
30	1.1E-04	8.3E-05	1.9E-03	2.8E-03	1.0E-04
Sum	5.4E-04	4.0E-04	9.1E-03	1.4E-02	4.9E-04
Life (years)	**1839**	**2494**	**110**	**72**	**2035**

Wind Analysis Summary

The results from the analytical wind analysis suggest that:

1. Maximum stresses in the truss occur at the two ends and are within the allowable limit for welded aluminum specified by AASHTO support specifications. Replacing the larger sign boards with smaller sign boards reduced the maximum stresses by 55%.
2. The nominal fatigue life of the critical members without consideration of the failed welded joints, exceeds the service life of the truss (typically 50 years).
3. The present fatigue analysis is performed assuming pristine state and no other factor except natural wind effecting fatigue performance. Several other factors such as diurnal temperature changes, truck gusts, subsequent corrosion of the members, weld deterioration etc., might affect the overall fatigue life of the structure. Truck gusts were assumed to have no statistically significant effect based on the work of (Li et al. 2006).

Thermal Effects

Structures subjected to large temperature variations on a daily basis are susceptible to thermal fatigue. Daily variations in temperature induce cyclic stresses in the structure components. This stress reversal causes the formation of microcracks in areas with higher stress concentrations, which gradually propagate leading to the fracture of component. A static thermal analysis was performed to investigate the effect of this phenomenon on the truss. The main goals of the thermal analysis were:

1. Develop an analytical model to compute the response of the truss to diurnal temperature changes.
2. Investigate the fatigue performance of the critical members and evaluate their fatigue life under the influence of daily temperature variations.

Thermal Loading

Changes in temperature causes expansion and/or contraction on any structure. In restrained (statically indeterminate) structures, this induces thermal stresses. The stress resulting from change in temperature is referred to as a thermal load. The source of temperature change can be direct sunlight, ambient outdoor air temperature, or temperature inside the structure. For this analysis, ambient air temperature is the only thermal loading source considered.

As the structure is exposed to diurnal temperature variations and is restrained at the bottom, thermal loads are considered. We know the basic equation from the strength of materials

$\Delta L = \alpha \Delta T L$

Where ΔL is the change in length, ΔT is the change in temperature in degrees Fahrenheit, L is the original length, and α is the coefficient of thermal expansion, $/^{\circ}F$, which depends on the material type.

Thermal Fatigue

The fatigue life of the pristine structure is calculated based on the data collected from finite element analysis. Using the stress ranges and number of cycles of the temperature range for 3 years, the fatigue life of the structure was found to be large compared to the expected service life. The following steps were carried out in the current study to find the thermal fatigue life:

1. Temperature data were collected from the National Climatic Data Center (NCDC).
2. A temperature time histogram was prepared and the corresponding number of cycles was found.

3. The derived temperature ranges were applied on the structure to calculate corresponding stress range.
4. The stress range generated was used in the above equations to calculate the fatigue life.

Temperature Distribution

Temperature range histogram was plotted by using a bin size of 5 degrees Fahrenheit. This was used to find the number of cycles of individual temperature ranges. Figure 5 shows the daily temperature range distribution.

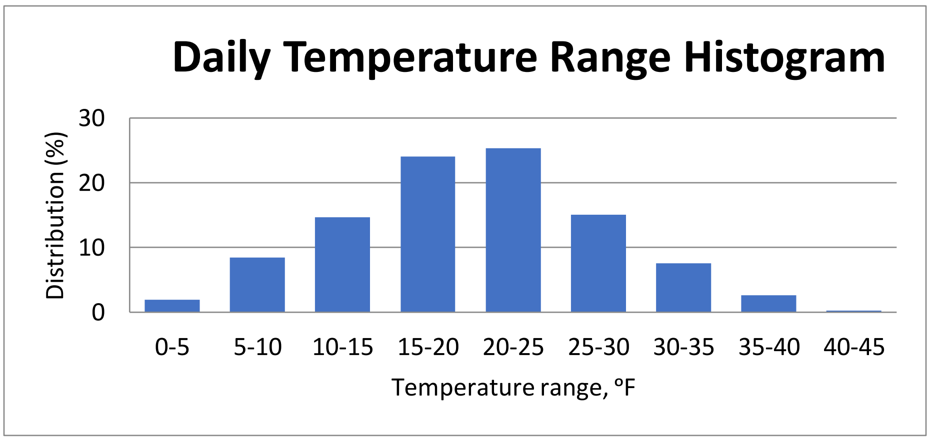


Figure 5: Daily Temperature-Range histogram

This graph was also used to find the number of cycles of each temperature range to calculate the damage to the structure. These temperature ranges were later applied on the structure to calculate corresponding thermal stresses and ultimately the fatigue life of the structure using S-N curve.

Thermal Analysis Summary

Below is the table showing stresses in each element due to the application of temperature.

Table 3: Thermal stresses for various temperature range

Stresses Range in Δ5°F increment, ksi					
Temperature Increment	Element D24	Element D47	Element C279	Element C280	Element C193
5	0.0246	0.1305	0.0636	0.097	0.117
10	0.0852	0.0857	0.2609	0.239	0.6622
15	0.1278	0.1287	0.1898	0.291	0.3511
20	0.1705	0.1713	0.253	0.388	0.4681
25	0.969	0.969	0.3163	0.485	0.5852
30	0.2557	0.257	0.3795	0.582	0.7022
35	0.2979	0.2998	0.4428	0.679	0.8192
40	0.3404	0.3427	0.5061	0.776	0.9362
45	0.383	0.3855	0.5693	0.873	1.0533

As the constant-amplitude fatigue limit (CAFL) is 0.44 ksi for diagonal members (elements D24 and D47) and 1.9 ksi for chord members (elements C279, C280 and C193) (AASHTO Support Specifications, 2015), but since the stresses in each element is lower than their corresponding CAFL values, it could be said that the fatigue life is large. However, for the sake of the study, the expected life of the critical members of the structure is calculated below.

From the stress values, using the general equation of the S-N curve for aluminum the number of cycles to failure at a given stress level is calculated. Then, using the Palmgren-Miner rule, accumulated damage is calculated for each stress range which is then summed to find total damage and fatigue life.

Table 4: Number of cycles to failure for corresponding thermal stresses

Temperature Increment (°F)	no of cycles	Element D24	Element D47	Element C279	Element C280	Element C193
5	21	2.3E+12	9.5E+09	1.01E+11	2.52E+10	1.4E+10
10	91	3.86E+10	3.8E+10	9.72E+08	1.3E+09	4.5E+07
15	159	1.02E+10	9.9E+09	2.77E+09	6.79E+08	3.7E+08
20	260	3.94E+09	3.9E+09	1.08E+09	2.63E+08	1.4E+08
25	274	12976974	1.3E+07	5.16E+08	1.26E+08	6.8E+07
30	163	1.04E+09	1E+09	2.83E+08	69416948	3.7E+07
35	82	6.28E+08	6.2E+08	1.71E+08	41806693	2.3E+07
40	28	4.05E+08	4E+08	1.1E+08	26945288	1.5E+07
45	3	2.75E+08	2.7E+08	74642229	18290179	9862826

Table 5 Total damage and life of the each elements

Element ID		Element D24	Element D47	Element C279	Element C280	Element C193
Total Damage	∑Di	1.81E-06	1.81E-06	7.59E-07	3.03E-06	6.04E-06
Life (years)		**553084**	**551193**	**1317153**	**330459**	**165457**

The expected fatigue life of the overhead sign support due to thermal loading is very large compared to the expected service life. There is minimal effect of the temperature change on the structure. Details of the thermal analysis are presented in Lucky, 2019.

Combined Wind and Thermal Fatigue Effects

Because the expected thermal fatigue life is very long, there is no need to formally combine the effects of wind and thermal fatigue. The truss failed before the expected fatigue life of a sound truss of this design exposed to the expected wind and thermal cycles at the location of the truss.

Material Testing

The goals of the material testing process were to:

1. Identify the probable immediate cause(s) of the truss failure.
2. Develop a working hypothesis as to the likely factors leading to the truss failure and suggest possible action(s) to address them.

Inspection of Failed Truss Sections

Following field inspection by ODOT personnel, the truss was cut into numbered sections and delivered to the University of Toledo for detailed examination. Visual inspection, microscopic analysis and material characterization were performed on exposed fracture surfaces and upon specific regions of interest. Visual inspection showed that the most dramatic fractures were all located along or adjacent to weld locations between the main truss chords and the cross members. Additionally, many of the welds appeared to be very non-uniform in thickness, shape and texture – contrary to most ideal aluminum welds described literature. This lead to a working hypothesis that the welds were related to the failure, possibly as the direct cause or a supporting factor.

Material Tests

With the hypothesis that the welds were a factor in the truss failure, detailed materials characterization work was performed with the following findings:

1. Scanning electron microscopy (SEM) of the fracture surfaces revealed that the fracture surfaces in the vicinity of at least two weld areas displayed features characteristic of fatigue assisted crack propagation (not shown here), with the crack initiation site being near the weld. Energy dispersive x-ray spectroscopy (EDS) of the surface also revealed regions where common highway environmental agents (e.g. road salts) had penetrated into the truss chord, possibly accelerating the failure via corrosion.
2. Energy dispersive x-ray spectroscopy (EDS) of the truss chord revealed the composition is an aluminum alloy with minor amounts of magnesium and silicon (most likely a 6xxx-series alloy). SEM and EDS also reveal that the alloy regions immediately next to the weld show changes in microstructure and elemental distribution, with the formation of magnesium and silicon-rich precipitates and other defects which could increase local brittleness.
3. Mounted cross sections of various welds from the truss were prepared for both visual and SEM examination.
    a. The weld nearest to the most severe truss fracture showed a high concentration of spherical voids dispersed throughout the weld as well as a highly interconnected network of micro-cracks between the voids (see Figure 6).

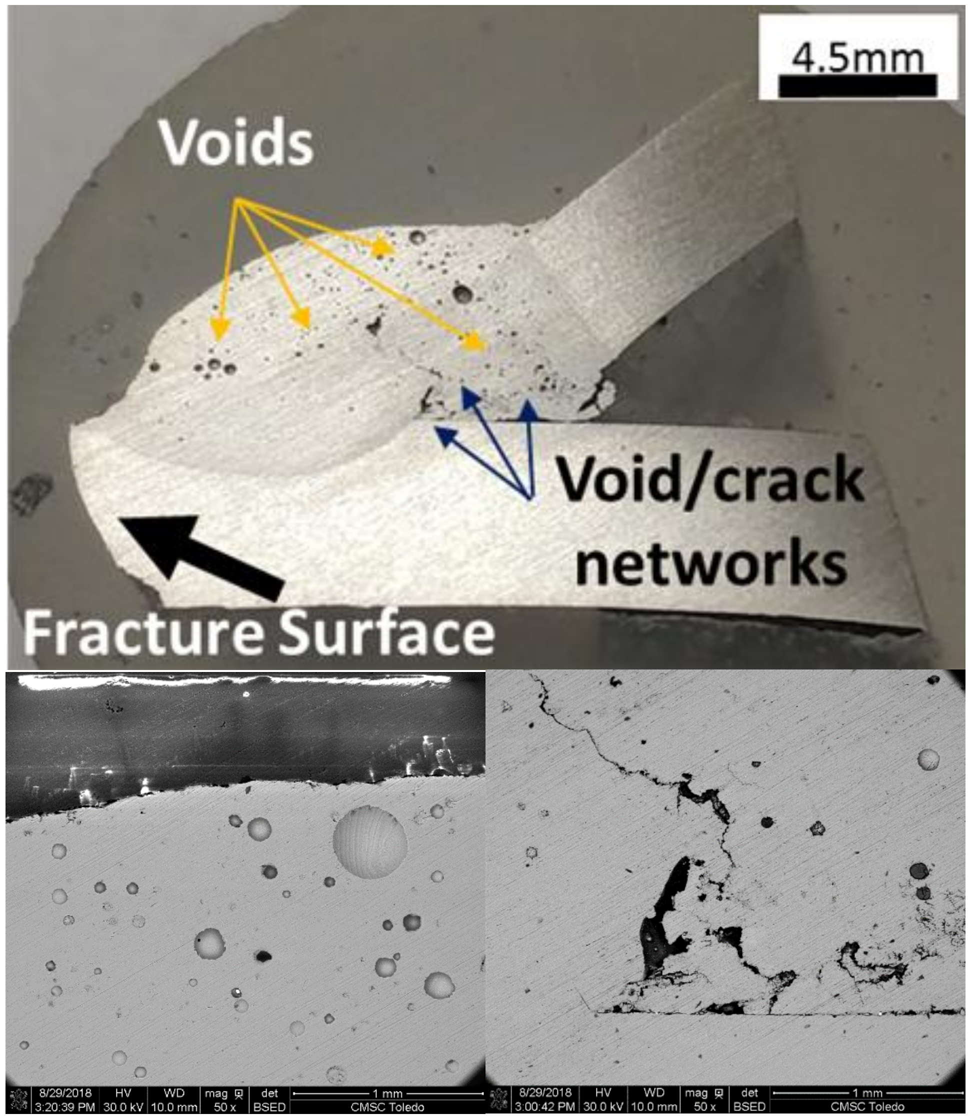


Figure 6: Optical image of weld cross section adjacent to fracture site (top), with electron micrograph images of voids (bottom left) and microcracks (bottom right) within weld.

b. Several welds from truss regions that were distant to any observed fractures were similarly examined. All of these welds showed the same presence of spherical voids through the weld but showed little to no evidence of micro-cracks (see Figure 7).

Figure 7: Optical images of weld cross sections from locations in truss distant from observed fractures showing presence of voids within welds

c. In general the extent of weld penetration at the various sites examined was highly variable and inconsistent – some of the welds had very slight penetration into the members being joined, while other welds were so thoroughly penetrated that any distinction of the original member shapes were lost locally.

Material Testing Summary

The findings from the material testing appear to confirm the hypothesis that the welds were a key cause of the truss failure. The overall weld quality for this truss appears to be relatively poor. The high concentration of spherical voids in the welds are typical for aluminum welds without sufficient cleaning of the metal surfaces prior to welding and/or insufficient protective inert gas blanketing the site during the welding operation. These factors lead to moisture and/or organic contaminents contacting the weld while it is still molten, during which time the contaminants decompose and elemental hydrogen dissolves into the molten alumnium. As the alumnium cools, hydrogen gas collects together to form microscopic pockets within the weld. Also, the presence of highly non-uniform weld thicknesses are also an indicator of poor welding fabrication practices. Regions with very heavy welds (with large, rough beading) also induce high thermal cycling into the surrounding alumnium alloys, which can weaken the local alloy strength.

The combination of the weld fabrication issues appear to have lead to an overall decrease in weld strength for the entire truss as well as an increase in physical defects that could be sites of crack initiation within the truss chords. High stresses at these regions would likely form microscopic cracks and the perdiocic cycling of these stresses during the service life of the truss would allow for crack propagation and eventual failure via fatigue. This is exacerbated by the fact that aluminum alloys, unlike steel, have no fundamental lower limit to the stress loading that can cause fatigure failure.

Conclusions & Recommendations

An overhead sign support truss on Alum Creek Drive at the I-270 interchange near Obetz, OH failed unexpectedly. Fatigue analyses for wind and temperature cyclic loading and material studies of the truss and the fracture areas were carried out. Weld fabrication issues appear to have caused physical defects within the welds that lead to the initiation of cracks. In and near high stress regions, these cracks propagated due to cyclic loading. This led to the observed fractures. Overall, it is likely the truss failed before the expected end of its service life due to weld fabrication problems.

Although it appears that the cause of the the failure for this specific truss (improper welding during truss fabrication/assembly) was identified, it is uncertain if this situation is representative of other trusses currently in service. Discussions with ODOT personel suggest that this truss was placed into service sometime in the late 1960’s or early 1970’s, with the exact date unknown along with the identity of the persons/group that performed the fabrication and installation. As such, there could be very many or very few similar to the trusses in service that are nearing the point of similar failure. To gain further insight into the actual extent and risk of this failure occuring again, the following actions are recommend:

1. Identify a number of trusses of a similar age (and possibly from a similar service region). These may be trusses that have been taken out of service or trusses still in service.
    a. For trusses that have been taken out of service, examination of the welds removed these trusses can be performed to determine if similar features (voids, micro-cracks, non-uniform beading, etc.) are present. Also, the extent of any cracking within these welds could be correlated to the approximate service lives of the trusses if the approximate start/end dates are known.

b. For a population of trusses that are in service, the first step would be hands on inspection of critical welds. For trusses whose foundations are on the ground, the critical welds would be near the truss ends. Critical welds that have uneven surfaces, that may be indicative of poor quality, could be subjected to nondestructive evaluation (NDE).

   There are several NDE techniques suited to examining aluminum welds, gamma ray, X-ray and phased array ultrasound. Implementation one of these techniques would require a test plan, validation of the plan and investigations into the accuracy of the selected techniques on overhead supports. The connection detail is complex and the access, traffic control and working conditions for overhead sign support structures are challenging. Field accuracy of the NDE would be substantially less than that achievable in the laboratory. Development of the test plan and validation should address whether the achievable accuracy is sufficient to make valid conclusions about the sign condition.

2. If these examinations reveal that the weld defects exist in other truss structures with comparable fabrication dates, a comprehensive plan should be developed quickly
   a. identify which structures still in service are most likely to have a similar fabrication history (year of fabrication and personnel involved), and
   b. conduct on-site examination of these trusses to determine if any signs of fatigue and/or other failures are in progress. Specific attention would be paid to the truss regions likely to experience high stresses as shown by the modeling results in this report. Any showing signs of imminent failure should be replaced as soon as possible.
3. A cost-benefit analysis may be required to determine a general compromise between two competing approaches:
   a. determining a service lifetime in which all aluminum-based trusses should be removed from service, regardless of the actual state of each individual truss, or
   b. allowing all trusses deployed during the same period (late 1960's to early 1970's) to remain in service and instituting a periodic inspection regimen such that each

truss is examined on-site on a regular basis to identify potential catastrophic failures before they occur.

Acknowledgements

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References

American Association of State Highway Transportation Officials, 2015, "LRFD Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals", 1st Edition with the 2017, 2018 and 2019 interims.

Haroon, A 2019, "Evaluation of Remaining Fatigue Life of a Non-Cantilever Highway Truss with Tubular Joints", MS Thesis, University of Toledo, Available through OhioLink after July 2019 https://www.ohiolink.edu/.

Huckelbridge, A. A., and Metzger, A. T. (2009). "Investigation of the Dayton, Ohio, IR 75 Sign Truss Failure of September 11, 2006." Journal of Performance of Constructed Facilities, 23(5), 372–378.

Li, X., Whalen, T. M., and Bowman, M. D. (2006). "Fatigue Strength and Evaluation of Sign Structures, Volume 1: Analysis and Evaluation." *Joint Transportation Research Program*, 1(June), 261.

K.C., L 2019, "Fatigue Calculation of Overhead Sign Structure for Thermal Loadings", MS Thesis, University of Toledo, Available through OhioLink after July 2019 https://www.ohiolink.edu/.