Aluminum Railcar Design and Useful Life – Fatigue Assessment

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BACKGROUND

The use of aluminum in the construction of rail passenger cars in the 1970's was a departure from traditional materials (e.g. stainless steel and steel) due to its strength to weight ratio and aesthetics. Various transit authorities adopted the aluminum rail vehicles for widespread use.

These early designed aluminum railcars are now more than 30 years old and are slowly approaching the end of their predicted useful life. Some of these cars could be exhibiting fatigue induced failures due to combination of unexpected load conditions and environmental factors that may shorten the remaining car body structure's life. Any desired structural strengthening of critical areas can be further inhibited by the nature of aluminum carbody design. However, due to other considerations outside the scope of engineering, a railcar useful life extension evaluation may be needed. This evaluation should include identification of high stress areas, load induced stress assessment, and both static and dynamic strain gauge testing of the railcar.

With the use of modern data acquisition equipment coupled with a better understanding of aluminum alloy properties, the ability to analyze the fatigue behavior of railcar structure has matured to the point where much more accurate predictions to useful life can be made.

This paper discusses fatigue analysis methodologies, data acquisition and data interpretation for predicting the car's useful service life. The overall results of testing, fatigue assessment, and measures to prolong useful life, including potential structural enhancement of critical areas are discussed.

RAILCAR STRUCTURE

Railcar shells are typically designed to meet or exceed a 30-35 year life. They can go through several overhauls of the railcar systems during that time, with minimum consideration given to the railcar body structure. Near the end of the design life however, a closer look at the railcar body structure may be warranted. Conservative structural design usually places the railcar structure to the safe side of the specified life expectancy, yet the stress analyses and stress tests performed on railcar structures never show the entire structure to be stressed evenly. As a result, the cumulative damage due to repeated cyclical stress on the structure will accumulate differently throughout the vehicle. High stress areas may have less remaining life than areas conforming to the predicted stress loads.

The critical areas are mostly located at a transition points between the relatively stiff end underframe structure of the car and the relatively flexible central underframe, mostly at the lower and upper door corners. This is also area of the expected highest vertical inflections. The carbody twist and the vertical passenger loads are the loads responsible for such a stress concentration.

REMAINING STRUCTURAL LIFE ASSESSMENT

There are two distinct phases of damage to a metal. The first is the *initiation phase* before cracks are initiated, and the second is the *propagation phase* after the initiation of a crack. In the second phase, the propagation phase, the progress of damage can be directly related to the crack length. During the initiation phase, the damage manifests itself in dislocations, slip bands, micro-cracks, etc. As a part of the analysis, the useful life of the structure can be considered to be entirely within the initiation phase, before the crack initiation. While there is often a useful life remaining in the car structure after a crack has initiated, it is generally defined that the useful life of any structure is declared consumed at the point when a crack is initiated.

The main goal of the task is to analyze the railcar body structure with conventional engineering test tools, in order to assess the current remaining life of the structure. The remaining life will be different at each location due to the differences in design and in cyclical stresses experienced at each point. To adequately address the current condition and predict remaining useful life, an assessment of railcar body structural integrity may be required. The assessment of remaining life can be accomplished through the non-destructive techniques (checking of critical location dimensions, and inspecting for signs of distortion and corrosion) on a representative sample, and *strain gauge testing* of selected railcar. This paper focuses on the strain *gauge testing* and life assessment.

STRUCTURAL TESTING

The structural testing should consist of two (2) steps involving a *static strain gauge test, dynamic strain gauge* test, and *accelerometer test*. The static strain gauge tests should include various load conditions including vertical bending at AW2 and diagonal jacking at AW0 load. The *dynamic strain gauge* and *accelerometer* tests should be run during actual operation over the revenue tracks. The static test can be completed at suitable maintenance facility. The dynamic test can be completed in two (2) phases. Phase I involves collecting operating data as the instrumented railcar travels on the selected revenue line to verify testing equipment and data acquisition. This test run should equate to approximately two (2) hours of data collection. Phase II involves testing the car as it operates on the selected revenue line. All strain gauge and accelerometer data should be recorded continuously for the duration of the test. As the time intervals need to be sufficiently small enough to enable accurate "rainflow" fatigue calculations and power density function calculations, a 500 Hz or better sampling rate should be used.

Instrumentation - Strain Gauge Locations

The selected railcar should be instrumented with a minimum of twenty-three (23) strain gauges about door corners 5 and 11. Figure 1 below illustrates the described locations.

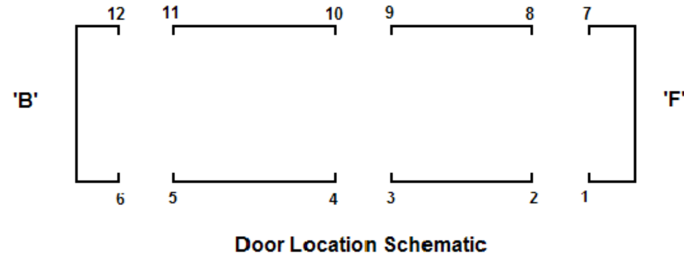


Figure 1. Door locations

The lower corners of doors 5 and 11 can be instrumented with eleven (11) strain gauges each. One (1) strain gauge may be installed on the upper corner of door 5. The layout and orientation of the strain gauges at each respective location is illustrated in the Figures 2 and 3.

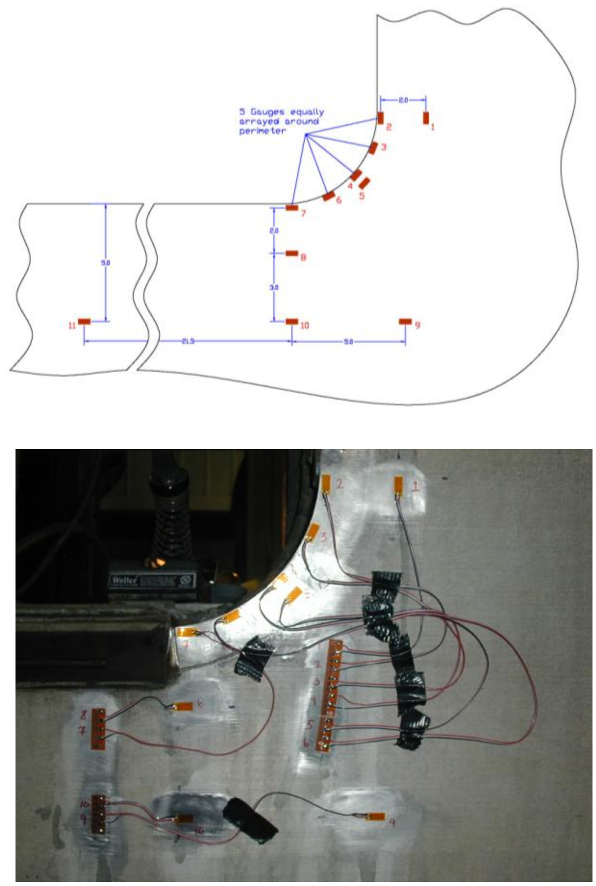
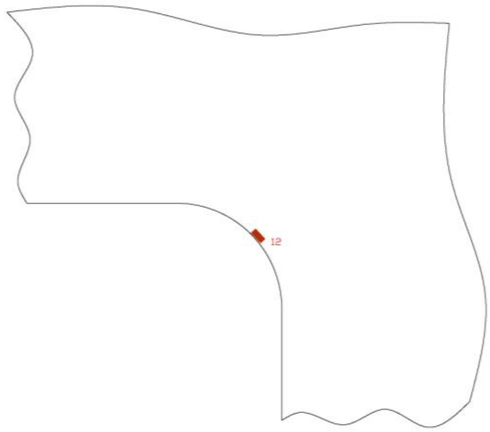


Figure 2. Door 5, Lower Corner Gauge Detail (11 gauges)



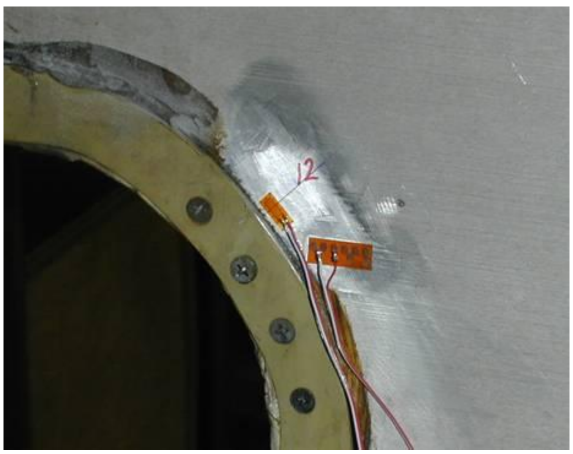


Figure 3. Door 5, Upper Corner Gauge Detail (1 gauge)

Strain Gauge and Data Acquisition System Specifications

The specifications for the strain gauges that may be used for the railcar testing are detailed in the Table 1.

Manufacturer	Vishay/Micro-Measurements
Type	CEA-13-250UN-350
Resistance	350 Ohm
Resistance Material	Constantan alloy
Base Material	Polymide
Gauge Factor	2.13 +/- 0.5%
Self-Temperature Compensation	13 (Aluminum)
Active Gauge Length	0.250”
Active Gauge Width	0.180”
Matrix Length	0.550”
Matrix Width	0.270”

Table 1. Strain Gauge Specifications

The strain gauges can be affixed to the carbody shell using Vishay/Micro-Measurements M-Bond 200 fast-curing adhesive. The gauges can be wired in a three wire quarter-bridge configuration using Belden #8723 signal cables that are terminated to the data acquisition equipment. Once terminated, all strain gauges need to be coated with a thick layer of RTV sealant to protect them from the environmental contamination and moisture during the dynamic testing. A 5VDC excitation can be supplied to the gauges for this test. Table 2 details the possible equipment used to collect, store, and validate the data during the tests.

EQUIPMENT	QTY	FUNCTION
SOMAT EDAQ Main Processor	1	Main base and processor for data acquisition boards.
SOMAT EDAQ High Level Accelerometer Board	1	Acquisition of accelerometer signals
SOMAT EDAQ Low Level Strain Gauge Board	3	Acquisition of strain gauge signals
DC Power Supply	1	Convert AC Power to provide power to DAQ system

Table 2. DAQ Equipment Details

Preliminary Test Results – Sample Analysis

A preliminary data analysis should be performed prior to removing equipment and ballast from the car to confirm validity of the results. The results of *both static tests* (diagonal jacking and vertical load tests) need to be within acceptable limits in terms of stress. The Table 3 summarizes the static test results, case study.

Load	Strain	Stress (calculated)
25,500 lbs. (Ballast), Applied Load	420 µ (measured)	4,242 psi
52,000 lbs. (AW0)	856 µ (calculated)	8,646 psi
77,500 lbs. (AW2)	1,276 µ (calculated)	12,888 psi
52,000 lbs. + 2” lift at jack pad	1,375 µ (calculated & measured)	13,888 psi
52,000 lbs + 3” lift at jack pad	1,652 µ (calculated & measured)	16,685 psi

Table 3. Measured and calculated strain and stress for Gauge #18 (lower corner door #11), where maximum stress concentration was expected.

Strains and the resultant stresses are based on a modulus of elasticity of 10.1x10^6 psi (Aluminum Design Manual), [1].

The *track (dynamic) tests* may show that the railcar is being cycled in both the vertical (primary) and twisting (secondary) modes, with twisting mode dominating the stress contribution. Figures 4 and 5 represent the strain traces of strain gauge #7 (lower door corner #5) and strain gauge #19 (lower door corner #11) for the stated condition. These gauges are located in the same position along the radius of their respective corners at opposite doors. This shows the relationship of what one side of the railcar is doing relative to the other side. The trace shown in red is strain gauge #7. Blue shows the trace of strain gauge #19.

As it can be seen on the graphs, the overall direction of the traces is opposite to each other indicating that the railcar is experiencing twist to the carbody structure. It can also be seen that the (relative) peaks of strain gauge #19 correspond to the (relative) troughs of strain gauge #7.

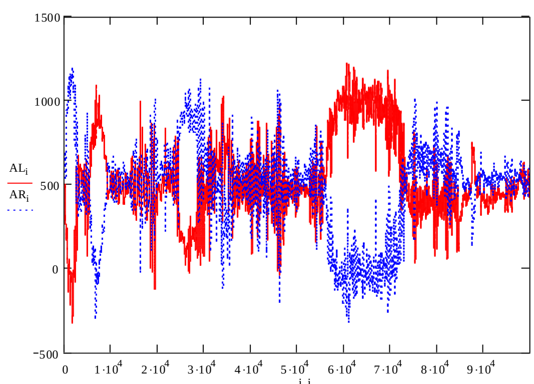


***Figure 4.** Strain Gauge Plot of Gauges 7 & 19 (opposite hand gauges), 3 ½ minute segment ~15 minutes after start.*

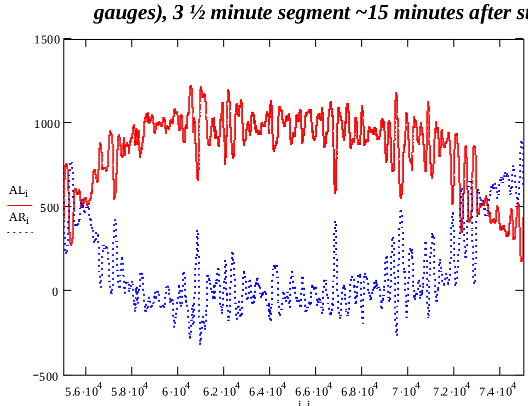


***Figure 5.** Close up view of above segment (40 sec.), Gauges are out of phase during extreme curve*

Preliminary *fatigue assessments* can be performed. This assessment assumes that the railcar runs at AW2 loading condition and that the selected line run is a duty cycle. The rainflow chart for mean and alternating strain is presented on the graph of Figure 6. The assessment also assumes that the material meets Aluminum Association minimum strength values.

With these assumptions, the predicted operating life is approximately 3,500 hours (or approximately one and a half years of operation). This value should not be construed as an absolute. It is only indicative of a relative order of magnitude, and indication of low cycle fatigue being the primary failure mechanism. From the Aluminum Design Manual, base metal has a fatigue limit of 10,200 psi (1,010 µ strain). The count of relatively high strain events (greater than 1,010 µstrain), is small.

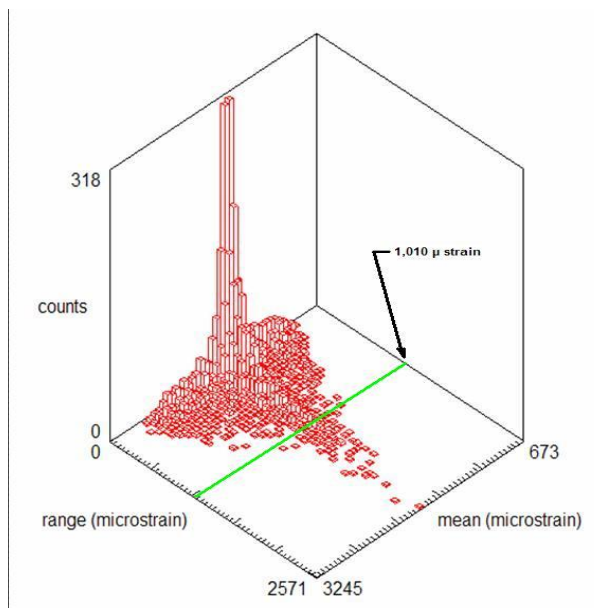


***Figure 6.** Rainflow Chart for mean and alternating strain (selected Line run)*

Final Analysis

The strain gauge data for the dynamic tests made on the selected lines can be analyzed to assess the fatigue life of the door corner area. This assessment assumes that the combined run (approximately 1¾ hours of running time) is a duty cycle. The strains can then be converted to stress by multiplying them by the modulus of elasticity (E), from the Aluminum Design Manual, E=10.1x10^6 psi. A "rainflow" counting method can be used to identify reversal points in the data to determine relative maximum and minimum stresses. Mean and alternating stresses can be then determined for each reversal cycle.

Two methods can be utilized to assess fatigue: a) *Stress Life Method* which uses Miner's Rule to calculate accumulated damage is highly empirical based on S-N (stress life) curves; where the S-N curves are determined from experimental data, and b) *Strain Life Method* based on fracture mechanics which examines the initiation and growth of small cracks at material discontinuities or at manufacturing defects. For both assessments, the material data (for 6061-T6 aluminum) is based on Fatigue Design Curves for 6061-T6 Aluminum (prepared by Oak Ridge National Laboratory), [2] MIL-HDBK-5H, Aluminum Design Manual [1], SAE Paper 840120 and the material analysis performed on samples by test laboratory.

The material properties used in both analyses can be adjusted to take into account the actual properties based on testing performed by test laboratory. Table 4 shows sample of possible test results.

Location	Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)
1	40,200	34,400	13
2	39,400	34,500	11
3	37,800	33,400	7
4	40,100	33,500	13
5	38,500	33,600	13
6	37,300	32,200	10

Table 4. Tested material properties

Per the Aluminum Design Manual and MIL-HDBK-5H, the minimum requirements are 38,000 psi for an ultimate tensile strength and 35,000 psi for yield strength. There is a slight but noticeable deviation between samples 5 and 6 (which are oriented in the same direction) and sample 6 (located in the radius) being lower. This degradation may be attributed to the damage incurred over a time. For purposes of this analysis, material properties (from location 6) were used. These samples were taken from the corresponding locations, Figure 7.

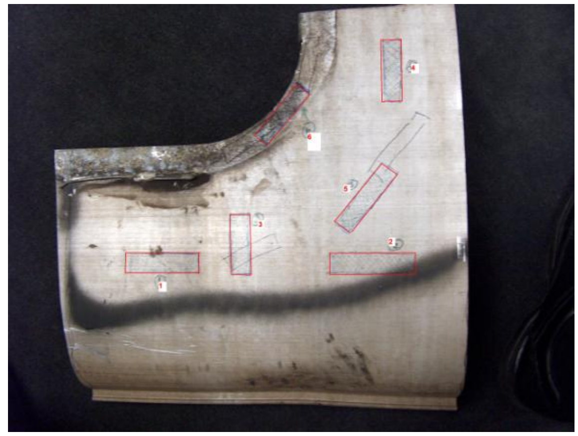


Figure 7. Material testing, sample location

It should be noted that aluminum does not exhibit a true endurance limit. Fatigue test results (as shown in MIL-HDBK-5H) go to 10^8 cycles where run-out is noted. Extrapolation much beyond this number (by an order of magnitude) is hypothetical. For the combined dynamic test runs on selected lines a total of 101,460 cycles may be recorded (which represents approximately 1¾ hours of running). For purposes of this analysis values beyond 10,000 hours are not considered as they may be unrealistic.

Surface Condition/Stress Concentration

Materials when fatigue tested are typically in a different condition (surface finish) than materials when actually used. An important part of the analysis is to "correct" the basic materials data to obtain an estimate of the fatigue limit of material in the area of interest. Fatigue cracks usually nucleate on the surface so that the condition of the surface plays a major role in the fatigue resistance. Fatigue test specimens are typically polished to eliminate this effect. To account for this, the material fatigue limit needs to be reduced.

Stress concentrations are one of the most important factors affecting the fatigue life. In the larger radius of the door corner, the stress concentration is accounted for directly, by the strain gauges. Stress concentrations due to surface condition (finish and corrosion) still need to be evaluated and considered in the analysis.

The surface finish of the car exterior could be a brushed finish and is estimated to be from 60 to 200 µ inches (Ra). Surface imperfections tend to be a "fissure" like inclusions characterized by relatively deep valleys compared to the radius at the bottom. For purposes of this analysis, it was assumed that the ratio of inclusion depth to the radius is 10. Imperfections due to corrosion tend to be deeper than those due to surface finish but the characteristic shape is more circular. For purposes of this analysis, it was also assumed that the ratio of inclusion depth to the radius is one.

The stress concentration factor, Kt, can be evaluated based on a semi-infinite plate with an elliptical notch as shown in the Figure 8. Stress is applied normal to the centerline of the notch. For (d/r) ratios of 10 and 1, the stress concentration factors (Kt) are evaluated as 7.75 and 3.16 respectively.

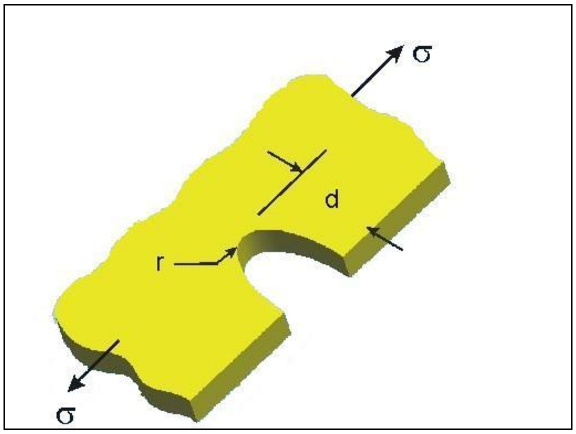


Figure 8. Semi-Infinite Plate with a Notch

The effective stress concentration in fatigue is typically less than that predicted by the stress concentration factor, Kt. This effective stress concentration factor is called the fatigue notch factor, Kf. The variation between the notch factor (Kf) and the stress concentration (Kt) is dependant on the size of the notch (the radius in particular) and the material. Higher strength materials are typically more sensitive to the notches. From Peterson "Notch Sensitivity", Metal Fatigue, the expression for Kf in terms of notch radius for aluminum (the fit of available test data) is:

$Kf = 1+ (Kt-1)/ (1+ (0.019/r))$, where "r" is the notch radius (inches).

For various surface conditions, the corresponding fatigue notch factors (Kf) were evaluated, Table 5.

Stress Life Approach

This approach uses Palmgren-Miner cumulative damage theory or Miner's Rule. Where n_1 is the number of cycles involving stress σ_1, n_2 at stress σ_2, and so forth, this rule is given as:

$$n_1/N_1 + n_2/N_2 + n_3/N_3 + \ldots n_t/N_t = 1$$

Where n_i is the number of cycles subjected to stress σ_i and N_i is the fatigue life related σ_i.

The equivalent stress analysis is further customized to take into account the lower tensile properties and it is modified by a ratio of the specified ultimate tensile strength to the actual tensile strength (38,000 psi /37,300 psi = 1.02).

Surface Condition	Depth (inches)	Radius (inches)	Stress Concentration Factor, Kt	Fatigue Notch Factor (Kf)
Extruded (200 Ra)	.0002	.00002	7.75	1.002
Pit	.002	.002	3.16	1.200
Pit	.005	.005	3.16	1.450
Pit	.010	.010	3.16	1.750
Pit	.015	.015	3.16	1.950
Pit	.020	.020	3.16	2.100

Table 5. Fatigue notch factor vs. surface condition

Strain Life Approach

Strain Life approach is based on the premise that the local stresses and strains around a stress concentration control the fatigue life. Fatigue damage is dependant on the local plastic strains around the stress concentrators. This approach uses a power relationship relating plastic strain cycles to the failure for a low cycle fatigue. This is combined with a relation to include the high cycle fatigue regime.

Results of the Analysis

For each surface condition, fatigue estimates are calculated using both the stress-life and strain-life approaches. These results are summarized on the Table 6.

Notch Factor, Kf	Stress Life (hours)	Strain Life (hours)
1.002	>10,000	>10,000
1.200	>10,000	>10,000
1.450	>10,000	8,928 (7,414 to initiate crack)
1.750	>10,000	2,915 (1,401 to initiate crack)
1.950	3,793	2,139 (625 to initiate crack)
2.100	1,829	1,890 (376 to initiate crack)

Table 6. Fatigue life vs. fatigue notch factor

The total hours shown in the strain life calculation include the time it takes to propagate a crack to a length of 0.160 or approximately one material thickness. Crack propagation is based on Paris' Law in a plane strain stress state.

It can be seen that a small increase in the notch factor (beyond 1.2) causes substantial reductions in the fatigue life estimates. The following Modified Goodman Diagrams, Figure 10 and 11 further illustrate this point. Note that in each of these, the Goodman Line is based on 10^8 cycles and modified for the actual yield strength.

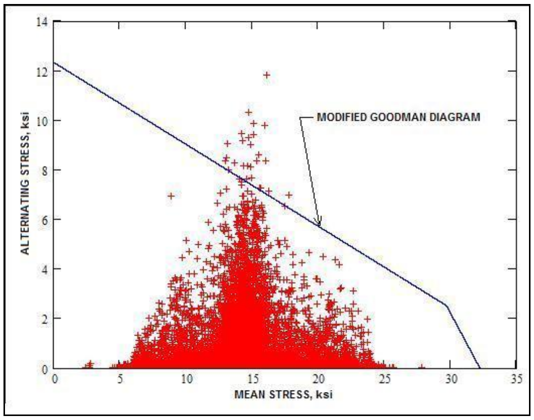


Figure 10. Modified Goodman Diagram with Kf = 1.00

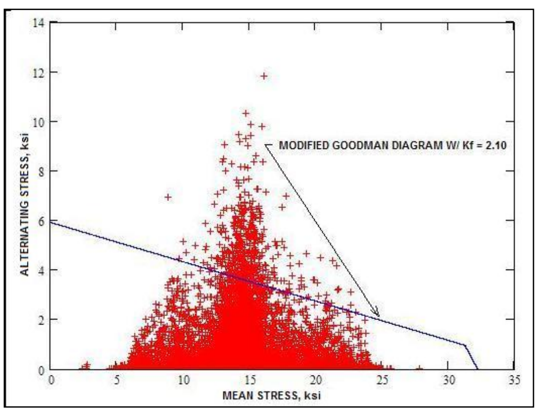


Figure 11. Modified Goodman Diagram with Kf = 2.10

Data points above the Goodman line have a negative operating margin and cause fatigue damage to the structure.

Even without the influence of the fatigue notches, there are still loads sustained that cause fatigue damage to the rail car structure. These loads are most likely result of the loss of the overall torsional stiffness of the car.

The results of the analysis should not be interpreted as absolute. It is indicative of a relative order of magnitude. The track data gathered could be limited and may not cover all track and loading conditions. Loads in excess of AW2 are typical during the peak hours. Had the car been loaded to AW4, then the peak stress would have been very close to or in excess of the yield strength. There may be other track/operating conditions that exist elsewhere on the system that could cause stresses beyond yield. The frequency of these types of overloads greatly affects the fatigue life of the structure. It may not be possible to assess how much fatigue damage any given structure has sustained to date. This is a function of a *degrading surface condition* and *loss of torsional stiffness*.

Carbody Torsional Stiffness

The floor panels provide torsional stiffness to the traditional rail car structure. Without the floor panels properly functioning in this role, especially near the door openings, the car body will behave as an open section. A load concentration may occur inboard of the bolsters where a relatively stiff section (which is supported by the carbody bolster) may abruptly transition to a relatively soft section which is mainly supported in shear by the plymetal flooring and cross bearers. Further inboard, the side wall section can be stabilized by the sidewall section (belt rail) between the side sill and window openings

During the testing phase it can be observed that the floor panels move transversely. This type of floor panel lateral movement can be indication that the railcar body is twisting. This can be confirmed with the strain gauge instrumentation readings.

STRUCTURAL ASSESSMENT

The strain gauge data can be examined and analyzed using two approaches and taking into account effects of the surface conditions. Under tested AW2 conditions and observed surface corrosion it can be estimated that the rail cars will last 2,000-5,000 hours (approximately 1-2 ½ years) from the time that the floor panels become loose enough that they are ineffectual from transmitting torsional load. Increased passenger load will shorten the fatigue life exponentially.

Surface condition may be viewed as influencing stress concentration on a micro scale. Surface finish (machining marks, scratches, brushing, etc.) and corrosion are the major factors to consider as well as the base material. It is from these types of surface defects where cracks tend to initiate. Stress concentration effects do increase rapidly as imperfection size increases (relative to the surface finish).

Analysis of the upper door corner (strain gauge #12) may not reveal anything notable. This is likely due to not being able to place the strain gauge close enough to the edge (as the mechanically fastened reinforcement may interfere with its placement).

CONCLUSIONS

The fatigue induced cumulative damage to the material microstructure is due to a combination of interacting factors that may influence the structural performance of the car shell and include loose floor panels and surface corrosion. These factors gradually adversely affect the fatigue strength of the structure. It is unlikely that these load conditions and operating environment were evaluated during the design phase of the car.

Since older series cars will likely be removed from service within the next five to ten years, the following structural enhancement can be necessary with this consideration in mind:

- Surface finish of the sides and edges of the door corners can be improved to an 80 Ra finish or better. Also approximately ⅛ inches of material from the edge of the inside radius can be removed (effectively increasing the door corner radius by ⅛ inches). This will have the effect of (at least partially) of "turning back the clock". This by itself is not a complete solution but should inhibit the formation of micro cracks.

- Maintain the carbody torsional stiffness by ensuring that the floor panels are properly affixed to the car shell structure.

ACKNOWLEDGEMENTS

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ENDNOTES

1. Aluminum Design Manual, The Aluminum Association, Inc., 1994.
2. Fatigue Design Curves for 6061-T6 Aluminum Oak Ridge National Laboratory, 1993