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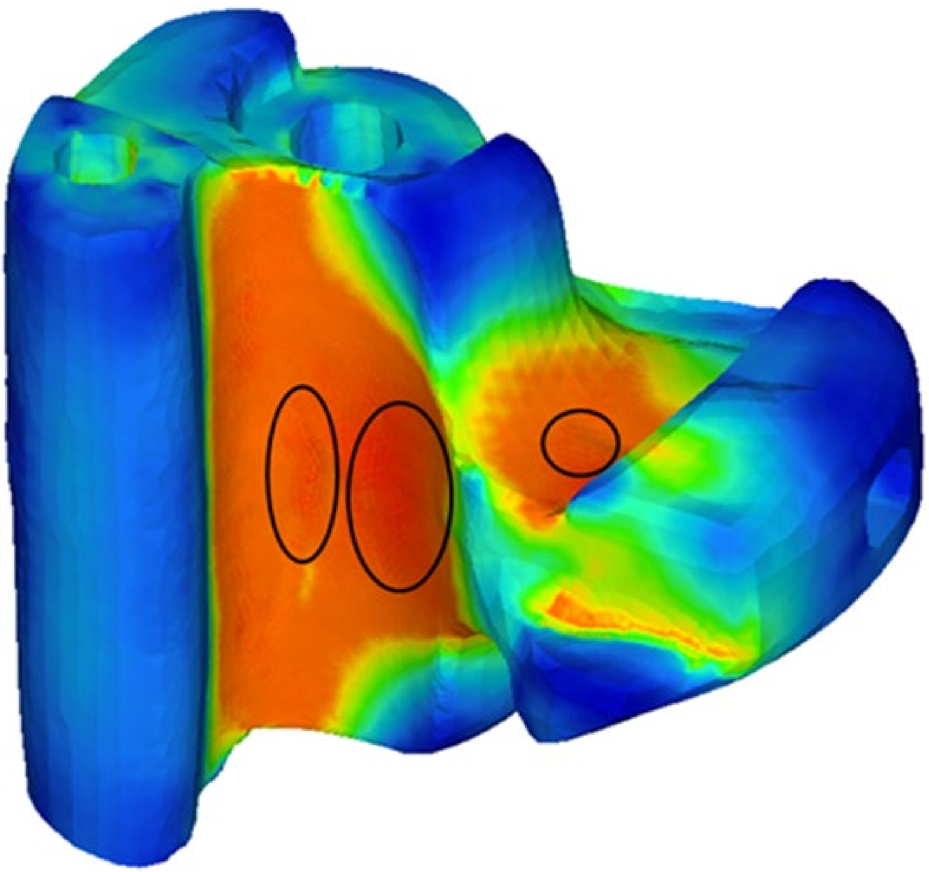
Office of Research,
Development and Technology
Washington, DC 20590

Enhancing the Safety Of Coupler Knuckles



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13. ABSTRACT (Maximum 200 words)

The primary objective of this research was to validate the finite element (FE) stress levels obtained during previous research through physical testing of a selected knuckle design. The validated FE model was used to investigate potential improvements in knuckle fatigue life, such as higher tensile strength material and design changes to critically-stressed knuckle locations.

Researchers found that the fatigue life of a coupler knuckle can be improved nearly 400 percent by increasing the tensile strength for M-201 Grade E steel from the present Association of American Railroads minimum of 120 ksi to 125 ksi. Increasing the thickness at two key locations in the studied knuckle increased the fatigue life by 83 percent even for the minimum tensile strength of 120 ksi for Grade E steel. A design of experiments approach for optimizing the knuckle based on the tensile strength, thickness of the inner face, and spacing of the cores at the flag hole is recommended. This method will find the optimum design parameter changes to achieve the best knuckle fatigue life possible under the geometry and weight constraints.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

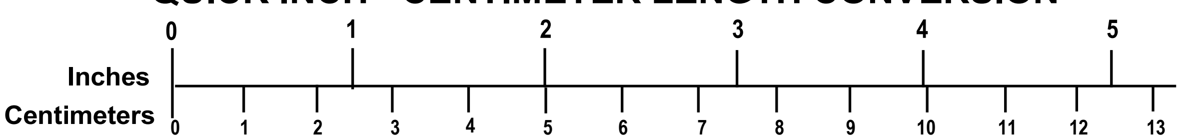
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

To make up trains, North American rail vehicles are connected using couplers. The coupler knuckle is intentionally designed to be the weakest link in the train because it is the most accessible component for inspection, maintenance, and replacement.

During train operation, the coupler knuckle experiences high buff (i.e., compressive) as well as draft (i.e., tensile) forces due to slack action in the train caused by train handling and changes in terrain. Given the rail industry's trend toward longer and heavier trains, these force levels are expected to be higher in the future.

When the buff or draft forces exceed the strength of a knuckle, it fails and causes the train to separate, causing separation of the brake line hose and resulting in an emergency brake application on the two separated portions of the train. Sometimes these undesired emergency applications result in derailments.

According to the Federal Railroad Administration (FRA) derailment database, broken coupler knuckles accounted for 102 derailments between 2000 to 2016, costing the industry over $10 million in damages and repairs. Such derailments, especially in trains carrying hazardous material, can lead to dangerous public safety consequences, especially if they occur in highly populated areas.

Although it is desirable to maintain the coupler knuckle as the weakest link in a train, FRA believes it would be beneficial to develop a better understanding of the stress levels within the knuckle and possible failure modes under varying coupler height mismatch and buff and draft force conditions.

The primary objective of this research was to validate the finite element (FE) stress levels obtained during previous research through physical testing of a selected knuckle design. The validated FE model was used to investigate potential improvements in knuckle fatigue life, such as higher tensile strength material and design changes to critically-stressed knuckle locations.

Researchers found that the fatigue life of a coupler knuckle can be improved nearly 400 percent by increasing the tensile strength for M-201 Grade E steel from the present Association of American Railroads minimum of 120 ksi to 125 ksi. Increasing the thickness at two key locations in the studied knuckle increased the fatigue life by 83 percent even for the minimum tensile strength of 120 ksi for Grade E steel.

The inclusion of even one cycle of increased loading of 300 kips maximum coupler force decreased the knuckle fatigue life by 8.9 percent. When the contact surface of the loading area was shifted either upward or downward by 3 inches for only 5 percent of the total cycles, the fatigue life of the knuckle was decreased by 9.4 percent.

Including a mere 5 percent offset loading on the knuckle decreased the fatigue life by nearly 10 percent. The knuckle geometry is not symmetric about the horizontal plane, and the upward shift of loading is worse than the downward shift. Of course, in any offset connection, one knuckle sees the upward shift (i.e., the loaded car) while the other knuckle sees the downward shift (i.e., the empty car).

The team recommends further study to optimize the changes in the coupler knuckle required to maximize fatigue life.

1 Introduction

1.1 Background

The mission of the Federal Railroad Administration (FRA) is to ensure the safe, efficient, and reliable movement of people and goods by rail through basic and applied research and the development of innovations and solutions.

In North American railroad operations, trains are made up of rail vehicles connected using couplers. The coupler knuckle is intentionally designed to be the weakest link in the train since it is most readily accessible for inspection, maintenance, and replacement in case of failure. A typical knuckle weighs approximately 80 lb, making it relatively easy for a train crew to handle when replacement is necessary.

During train operations, the knuckle experiences high buff (i.e., compressive) and draft (i.e., tensile) forces due to slack action in the train caused by train handling and changes in terrain. These forces can be steady state or dynamic in nature, depending on the terrain and how the train is being handled. Given the rail industry trend toward longer and heavier trains, these force levels are expected to increase and be sustained for longer durations.

When the buff or draft forces exceed the strength of a knuckle, it fails and causes the train to break in two, causing separation of the train line hoses. Failure can also occur if the fatigue life of the knuckle is exceeded. Knuckle failure and train separation ultimately result in an emergency brake application, and such an event may also cause a derailment. In fact, according to the FRA derailment database, broken knuckles accounted for 102 derailments between 2000 and 2016, costing the industry nearly $10 million in damages and repairs. Such derailments, especially in trains carrying hazardous material, can lead to dangerous public safety consequences, especially if they occur in a highly populated area. These events already result in significant operational issues for the industry.

To develop a better understanding of the stress levels within the knuckle and possible failure modes under varying coupler height mismatch and buff and draft force conditions, FRA sponsored Sharma & Associates, Inc. to investigate knuckle design modifications which would lead to longer fatigue life.

1.2 Objectives

The primary objective of this research was to develop a better understanding of the forces and stresses within a knuckle and determine the probable failure modes of a knuckle under varying coupler height mismatch and varying buff and draft force conditions.

1.3 Overall Approach

The research effort focused on validating previous FE stress level predictions using the measured data obtained from knuckle testing. The team procured a candidate knuckle for instrumentation and testing using strains and stress levels for various load levels to validate the FE model. The team then proposed knuckle design modifications to enhance knuckle safety and evaluated the modifications through FE and fatigue analyses.

1.4 Scope

The scope of the effort was twofold. First, the team reviewed coupler knuckle failure incidences, trends in failure, and major underlying failure mechanism(s). Based on the knowledge and understanding gained, a strategy to conduct controlled tests was proposed for physical testing. A test study was then executed, followed by model validation. The model simulations were used to investigate knuckle design features that could improve fatigue life.

1.5 Organization of the Report

Section 2 presents the development of instrumentation for the chosen knuckle type and describes the tests that the team conducted. Section 3 discusses how the team used the test data to validate the FE model, and Section 4 describes the fatigue life estimates developed per industry standards. Section 5 discusses the possible effect of material strength and geometric parameters on fatigue life. Conclusions and recommendations for further research and analyses are included in Section 6.

2 Knuckle Instrumentation and Testing

2.1 Knuckle Instrumentation

Researchers instrumented an E-type knuckle, the most common in the U.S. rail fleet, with five uniaxial strain gages (see Figure 1). Each gage was labeled "SG" followed by a single digit. The strain gage locations were selected using the highest stress locations from previous FE predictions. The accuracy of the strain gages is 0.5 percent full scale (FS), or 3,000 X 0.005 = 15 µe. The instrumented E-type knuckle was installed in a coupler provided by Miner Enterprises and the testing was conducted in its loading machine. The ring welded to the coupler shown in the left photograph was used for the ease of handling the coupler.

A SoMat eDAQLite data acquisition unit was used to collect all measurements. The load cell force signal from the loading testing machine was also recorded. All measurements were recorded at 100 samples per second.

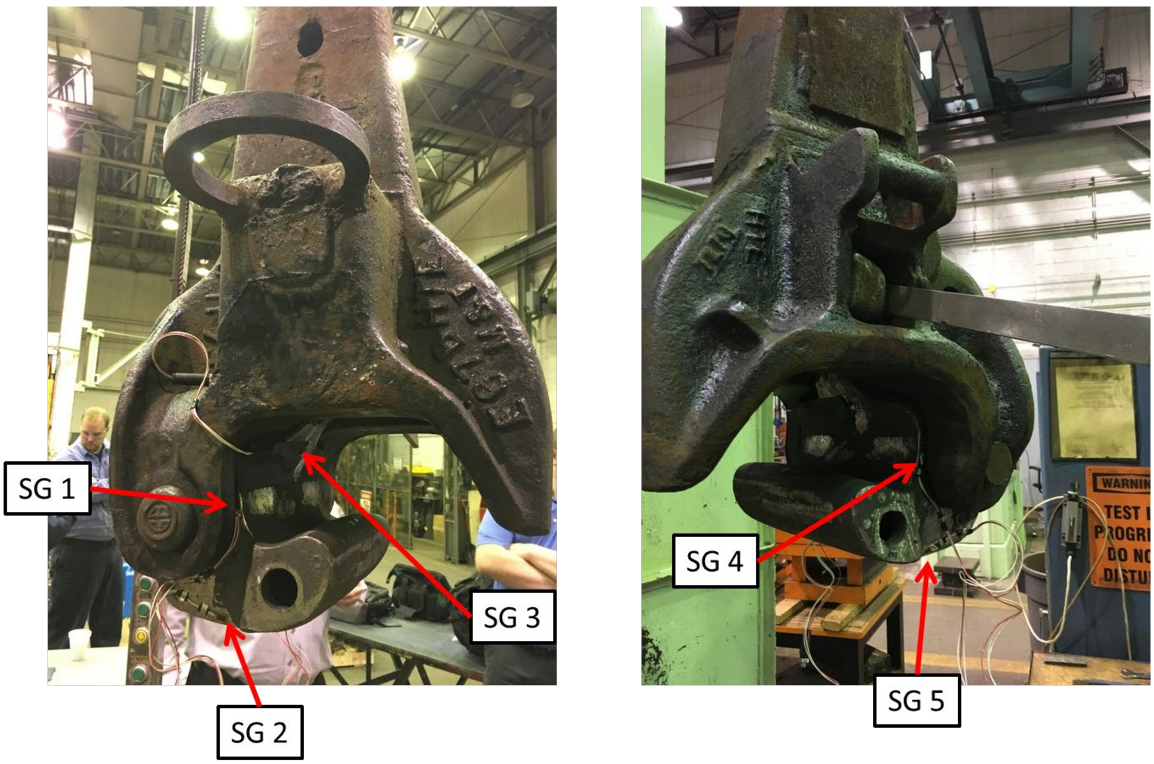

Figure 1. Strain gage locations on instrumented knuckle installed in loading machine

2.2 Knuckle Testing

All testing was conducted at Miner Enterprise's facility in Geneva, Illinois, using a 1,000,000-lb. coupler loading machine to apply the loads to the instrumented E-type knuckle in tension (tension is the most common mode of knuckle failure). The loads applied to the knuckle are listed in Table 1 and are a subset of the loads prescribed for fatigue testing in AAR MSRP specification M-216, "Knuckles, Types E and F – Fatigue Test" (Table 4.1) and "Knuckle fatigue test load cycles" in [1]. Since the coupler loading machine accuracy is 1 percent of full scale (±10,000 lb), the 17-kip load in M-216 was omitted because it is very similar to the 18-kip load. The difference between these two loads is well within the accuracy limit of the loading system and thus could be ignored in testing. The higher loads produce higher stresses and thus are more important when validating the results of the FE simulations.

The loads given in Table 1 were applied to the instrumented knuckle beginning with the lowest load and proceeding to the highest load, stopping at each level for about 30 seconds to provide a stable level for obtaining an average stress at that load. Once the maximum load was achieved, the knuckle was unloaded by applying each load in the table from highest to lowest load, again stopping at each level for approximately 30 seconds. Applying the loads in both increasing and decreasing order shows the effects of any hysteresis in the system. This loading sequence was conducted three times.

Table 1. Loads for knuckle testing

Step	Load, kips
1	15
2	18
3	59
4	79
5	97
6	115
7	133
8	154
9	171
10	189
11	209
12	227
13	245
14	265
15	283

The measured loads for each of these steps is shown in Table 2. The range of actual loads taking into account the load machine accuracy is shown in Table 3, Table 4, and Table 5 for tests 1, 2, and 3, respectively. At the highest load targeted for this test, the potential error in the actual load was only about 3.5 percent of the total load applied. At the lower loads the strain, and hence the stress, in the knuckle is very low and therefore not significant for the fatigue life.

Table 2. Measured loads for all three tests

Step	Target Load, kips	Test 1 Measured Load, kips	Test 2 Measured Load, kips	Test 3 Measured Load, kips
1	15	14.7	14.7	14.9
2	18	18.2	18.8	17.9
3	59	59.0	59.4	58.9
4	79	78.8	79.2	79.3
5	97	96.7	97.8	96.5
6	115	114.6	114.6	114.9
7	133	132.8	133.5	133.1
8	154	153.7	154.4	154.3
9	171	170.7	170.8	171.3
10	189	188.6	188.6	189.0
11	209	208.8	208.7	209.2
12	227	226.6	227.3	227.0
13	245	244.9	244.5	244.7
14	265	264.7	265.2	264.7
15	283	282.5	282.8	282.5
16	265	264.9	265.4	264.9
17	245	244.9	244.2	244.3
18	227	226.5	226.5	226.6
19	209	209.2	209.0	208.5
20	189	189.1	189.6	188.8
21	171	171.3	170.9	170.3
22	154	154.3	154.5	153.8
23	133	133.2	133.4	132.3
24	115	115.3	114.5	114.6
25	97	97.2	96.8	97.0
26	79	79.9	78.7	78.9
27	59	59.7	59.4	59.2
28	18	18.1	17.8	18.1
29	15	14.9	15.3	15.0

Table 3. Test 1 loading extremes, taking into account load machine accuracy[1]

Step	Target Load, kips	Measured Load, kips	Minimum Load, kips	Percentage Difference	Maximum Load, kips	Percentage Difference
1	15	14.7	4.7	68.03	24.7	68.03
2	18	18.2	8.2	54.95	28.2	54.95
3	59	59.0	49.0	16.95	69.0	16.95
4	79	78.8	68.8	12.69	88.8	12.69
5	97	96.7	86.7	10.34	106.7	10.34
6	115	114.6	104.6	8.72	124.6	8.72
7	133	132.8	122.8	7.53	142.8	7.53
8	154	153.7	143.7	6.51	163.7	6.51
9	171	170.7	160.7	5.86	180.7	5.86
10	189	188.6	178.6	5.30	198.6	5.30
11	209	208.8	198.8	4.79	218.8	4.79
12	227	226.6	216.6	4.41	236.6	4.41
13	245	244.9	234.9	4.08	254.9	4.08
14	265	264.7	254.7	3.78	274.7	3.78
15	283	282.5	272.5	3.54	292.5	3.54
16	265	264.9	254.9	3.77	274.9	3.77
17	245	244.9	234.9	4.08	254.9	4.08
18	227	226.5	216.5	4.41	236.5	4.41
19	209	209.2	199.2	4.78	219.2	4.78
20	189	189.1	179.1	5.29	199.1	5.29
21	171	171.3	161.3	5.84	181.3	5.84
22	154	154.3	144.3	6.48	164.3	6.48
23	133	133.2	123.2	7.51	143.2	7.51
24	115	115.3	105.3	8.67	125.3	8.67
25	97	97.2	87.2	10.29	107.2	10.29
26	79	79.9	69.9	12.52	89.9	12.52
27	59	59.7	49.7	16.75	69.7	16.75
28	18	18.1	8.1	55.12	28.1	55.12
29	15	14.9	4.9	67.17	24.9	67.17

[1] The loading machine accuracy is ±1 percent of full scale (±10 kips).

Table 4. Test 2 loading extremes, taking into account load machine accuracy

Step	Target Load, kips	Measured Load, kips	Minimum Load, kips	Percentage Difference	Maximum Load, kips	Percentage Difference
1	15	14.7	4.7	68.11	24.7	68.11
2	18	18.8	8.8	53.09	28.8	53.09
3	59	59.4	49.4	16.84	69.4	16.84
4	79	79.2	69.2	12.62	89.2	12.62
5	97	97.8	87.8	10.22	107.8	10.22
6	115	114.6	104.6	8.73	124.6	8.73
7	133	133.5	123.5	7.49	143.5	7.49
8	154	154.4	144.4	6.48	164.4	6.48
9	171	170.8	160.8	5.85	180.8	5.85
10	189	188.6	178.6	5.30	198.6	5.30
11	209	208.7	198.7	4.79	218.7	4.79
12	227	227.3	217.3	4.40	237.3	4.40
13	245	244.5	234.5	4.09	254.5	4.09
14	265	265.2	255.2	3.77	275.2	3.77
15	283	282.8	272.8	3.54	292.8	3.54
16	265	265.4	255.4	3.77	275.4	3.77
17	245	244.2	234.2	4.10	254.2	4.10
18	227	226.5	216.5	4.41	236.5	4.41
19	209	209.0	199.0	4.79	219.0	4.79
20	189	189.6	179.6	5.27	199.6	5.27
21	171	170.9	160.9	5.85	180.9	5.85
22	154	154.5	144.5	6.47	164.5	6.47
23	133	133.4	123.4	7.50	143.4	7.50
24	115	114.5	104.5	8.73	124.5	8.73
25	97	96.8	86.8	10.33	106.8	10.33
26	79	78.7	68.7	12.71	88.7	12.71
27	59	59.4	49.4	16.85	69.4	16.85
28	18	17.8	7.8	56.24	27.8	56.24
29	15	15.3	5.3	65.37	25.3	65.37

Table 5. Test 3 loading extremes, taking into account load machine accuracy

Step	Target Load, kips	Measured Load, kips	Minimum Load, kips	Percentage Difference	Maximum Load, kips	Percentage Difference
1	15	14.9	4.9	67.14	24.9	67.14
2	18	17.9	7.9	55.73	27.9	55.73
3	59	58.9	48.9	16.97	68.9	16.97
4	79	79.3	69.3	12.62	89.3	12.62
5	97	96.5	86.5	10.36	106.5	10.36
6	115	114.9	104.9	8.70	124.9	8.70
7	133	133.1	123.1	7.51	143.1	7.51
8	154	154.3	144.3	6.48	164.3	6.48
9	171	171.3	161.3	5.84	181.3	5.84
10	189	189.0	179.0	5.29	199.0	5.29
11	209	209.2	199.2	4.78	219.2	4.78
12	227	227.0	217.0	4.41	237.0	4.41
13	245	244.7	234.7	4.09	254.7	4.09
14	265	264.7	254.7	3.78	274.7	3.78
15	283	282.5	272.5	3.54	292.5	3.54
16	265	264.9	254.9	3.78	274.9	3.78
17	245	244.3	234.3	4.09	254.3	4.09
18	227	226.6	216.6	4.41	236.6	4.41
19	209	208.5	198.5	4.80	218.5	4.80
20	189	188.8	178.8	5.30	198.8	5.30
21	171	170.3	160.3	5.87	180.3	5.87
22	154	153.8	143.8	6.50	163.8	6.50
23	133	132.3	122.3	7.56	142.3	7.56
24	115	114.6	104.6	8.73	124.6	8.73
25	97	97.0	87.0	10.31	107.0	10.31
26	79	78.9	68.9	12.67	88.9	12.67
27	59	59.2	49.2	16.88	69.2	16.88
28	18	18.1	8.1	55.16	28.1	55.16
29	15	15.0	5.0	66.48	25.0	66.48

An example of the applied loading and measured strains for the first test is shown in Figure 2. All the strains showed a linear relationship with the applied load, although each gage location had a different slope due to the varying knuckle strength (i.e., different thicknesses) at these locations. The strains for gages SG2 and SG5 were compression, hence the negative values.

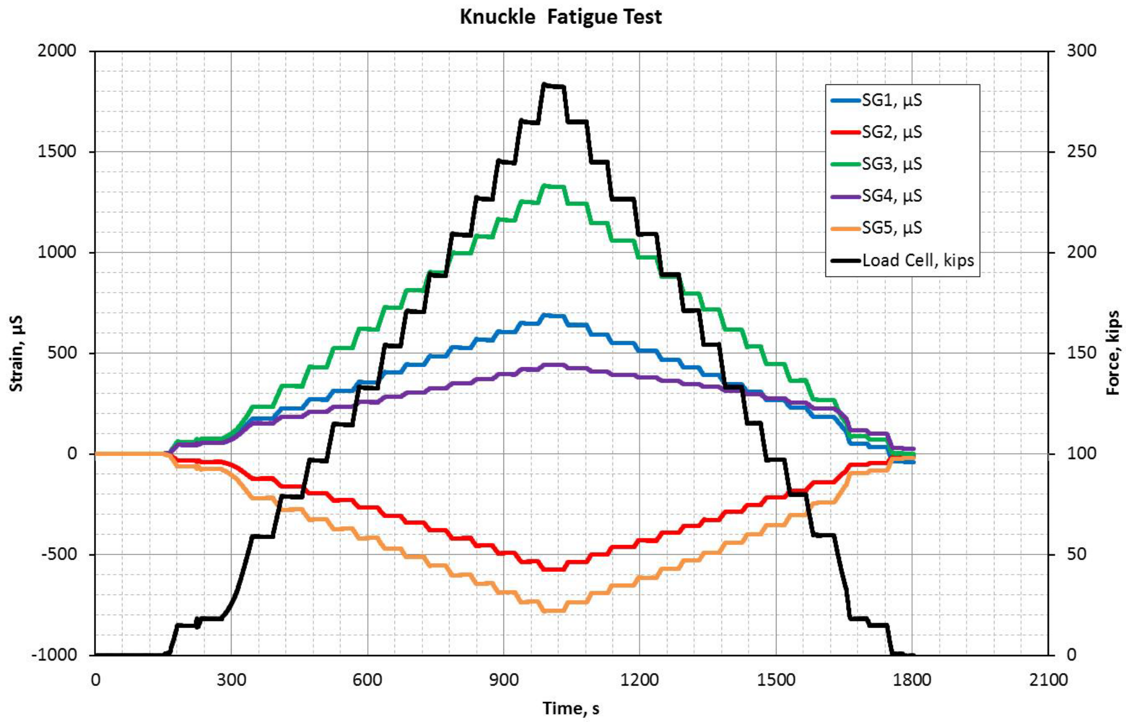

Figure 2. Example time history of knuckle test results

2.3 Data Processing and Test Results

Average steady state strains were calculated over 30-second averaging intervals. Table 6 shows the steady state loads and the averaged strains for the three tests. SG2 and SG5 were in compression during draft loading. SG3 showed the greatest response to the knuckle loading, so the validation portion of this report will focus on that strain gage.

These average strain values were then cross-plotted with the loads to further analyze the relationship between strain and load. Figure 3 shows the SG1 loading curve, Figure 4 shows the SG3 loading curve, and Figure 5 shows the SG4 loading curve. Almost no hysteresis is present for SG1 and SG3 and the curves show that the relationship between strain and load is linear. However, SG4 shows erratic behavior, with significant hysteresis and differences between tests. Therefore, the team concluded that the results from SG4 are not consistent and no comparison with the FE model results were made at this location.

Table 6. Averaged loading and averaged strains over all three tests

Step	Target Load, kips	Load Cell, Reading, kips	**SG1, με**	SG2, με	**SG3, με**	SG4, με	SG5, με
1	15	14.8	**46.4**	-31.9	***61.8***	36.8	-54.2
2	18	18.3	**57.8**	-40.2	***77.1***	45.2	-67.8
3	59	59.1	**174.3**	-123.4	***244.0***	129.9	-196.4
4	79	79.1	**221.3**	-160.9	***337.5***	157.4	-249.6
5	97	97.0	**262.0**	-194.3	***426.8***	179.2	-295.3
6	115	114.7	**301.7**	-227.3	***515.7***	200.2	-339.5
7	133	133.1	**342.6**	-261.9	***608.2***	221.8	-384.9
8	154	154.1	**388.8**	-301.6	***713.1***	246.3	-435.8
9	171	170.9	**425.5**	-333.6	***796.9***	265.9	-476.2
10	189	188.7	**464.3**	-367.6	***885.0***	286.9	-518.8
11	209	208.9	**508.0**	-406.3	***983.9***	311.3	-566.7
12	227	226.9	**547.9**	-441.4	***1071.8***	333.1	-609.5
13	245	244.7	**588.1**	-476.1	***1157.8***	354.9	-651.3
14	265	264.9	**635.7**	-516.1	***1255.1***	380.7	-699.4
15	283	282.6	**677.9**	-551.4	***1333.1***	405.8	-742.4
16	265	265.1	**635.0**	-516.6	***1248.6***	391.3	-702.5
17	245	244.4	**586.9**	-476.8	***1149.0***	373.6	-655.9
18	227	226.5	**548.5**	-443.2	***1063.7***	358.8	-616.5
19	209	208.9	**512.0**	-410.3	***980.1***	344.2	-577.7
20	189	189.2	**471.3**	-373.6	***886.3***	327.4	-533.9
21	171	170.8	**433.6**	-339.6	***799.2***	311.6	-493.0
22	154	154.2	**399.4**	-308.9	***720.1***	297.3	-455.5
23	133	133.0	**355.6**	-269.4	***618.9***	278.6	-406.8
24	115	114.8	**318.1**	-235.6	***532.6***	261.5	-364.1
25	97	97.0	**281.3**	-202.1	***448.0***	243.5	-320.6
26	79	79.2	**243.7**	-167.8	***363.4***	223.9	-274.9
27	59	59.4	**200.6**	-129.1	***268.2***	199.5	-221.1
28	18	18.0	**79.9**	-43.2	***86.3***	101.3	-82.8
29	15	15.1	**64.8**	-37.3	***72.0***	85.2	-71.2

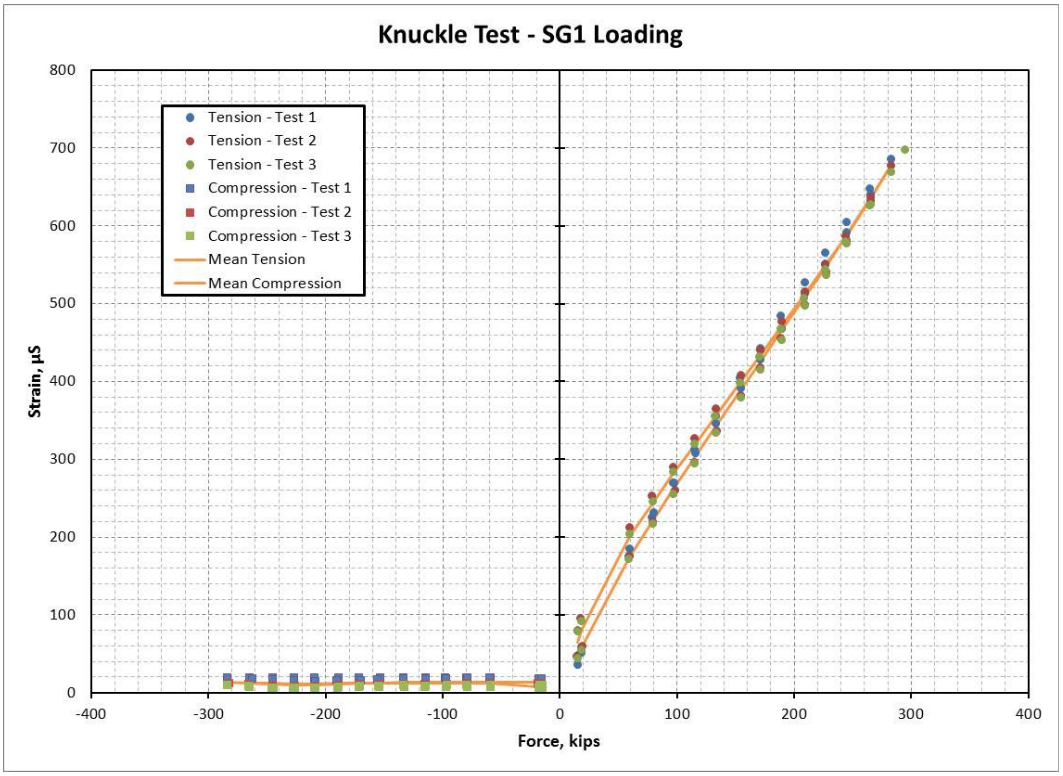

Figure 3. SG 1 test results

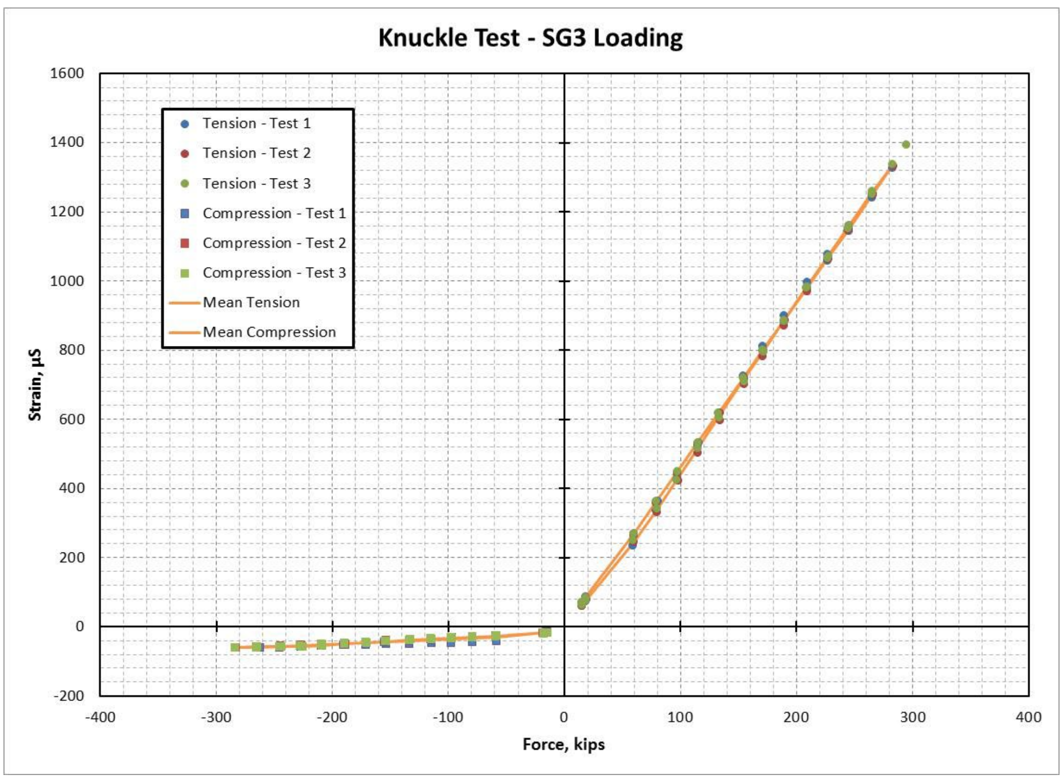

Figure 4. SG 3 test results

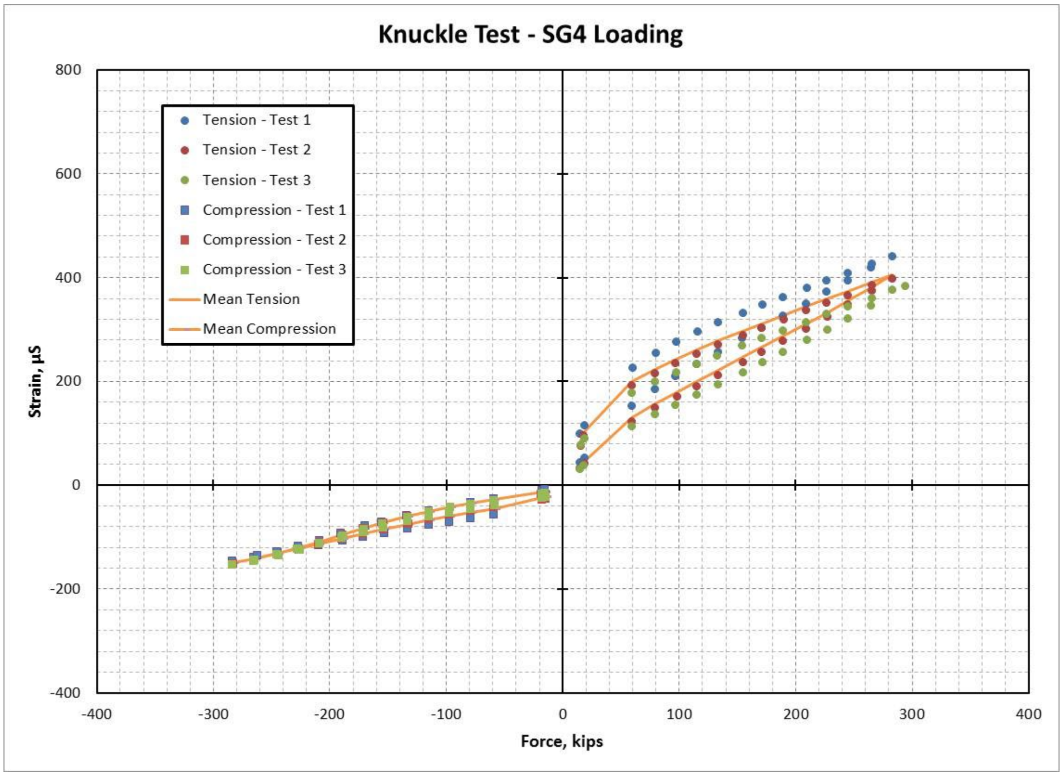

Figure 5. SG 4 test results

3 Knuckle Finite Element Model Validation

The FE model used in the coupler knuckle safety enhancement project is shown in Figure 6. The maximum principal stress (P1) is shown for the load case corresponding to the maximum test load of 283 kips. The FEA model had 108,062 elements and 168,043 nodes. Solid 187, 2nd order 10-node tetrahedral elements were used. This element had three degrees of freedom at each node. Plasticity, stress stiffening, large deflection, and strain were modeled. A finer element size (3 mm) was used in critical, high stress areas, such as the pulling face and pulling lug. HyperWorks® was used in pre-processing and post-processing [3]. ANSYS® was used as a solver [4].

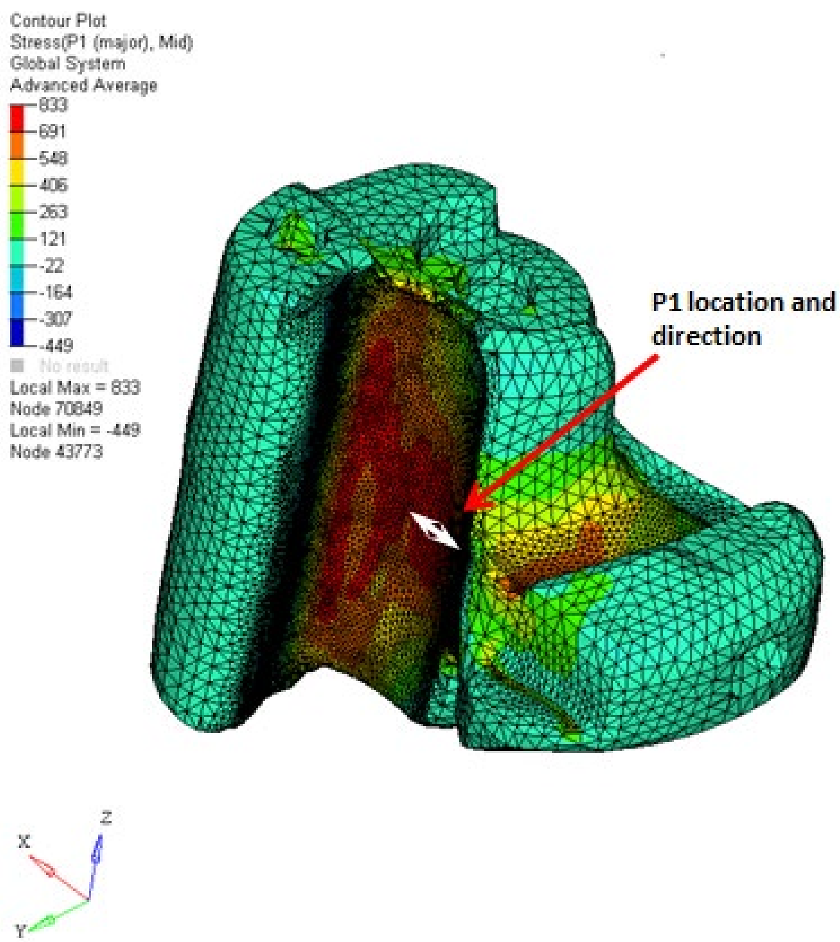

Figure 6. Mesh analysis on knuckle showing maximum principal (P1) stress for 283-kip load case

The values for the P1 stress at the location of strain gages 1 (SG1) and 3 (SG3) were extracted and averaged over the surface area corresponding to the physical size of the strain gage for each of the loads in Table 1. The stresses from at least seven nodes in the FE model at the strain gage location were averaged to obtain the stress to be compared to the stress measured by the strain gage. These stresses were then converted to strains and compared to the averaged strains from the test data (see Table 7).

Table 7. Comparison between FE P1 strains and test strains for SG3

Load, kips	FEA P1 Average Strain at SG1, με	Average Strain at SG1 from Test, με	FEA P1 Average Strain at SG3, με	Average Strain at SG3 from Test, με
15	27.5	0.0	76.3	61.8
18	40.0	7.8	90.0	77.1
59	125.0	124.3	297.5	244.0
79	167.5	171.3	397.5	337.5
97	205.0	212.0	490.0	426.8
115	240.0	251.7	580.0	515.7
133	282.5	292.6	673.8	608.2
154	327.5	338.8	781.3	713.1
171	362.5	375.5	867.5	796.9
189	400.0	414.3	961.3	885.0
209	445.0	458.0	1063.8	983.9
227	480.0	497.9	1157.5	1071.8
245	520.0	538.1	1252.5	1157.8
265	560.0	585.7	1356.3	1255.1
283	597.5	627.9	1448.8	1333.1
265	560.0	585.0	1356.3	1248.6
245	520.0	536.9	1252.5	1149.0
227	480.0	498.5	1157.5	1063.7
209	445.0	462.0	1063.8	980.1
189	400.0	421.3	961.3	886.3
171	362.5	383.6	867.5	799.2
154	327.5	349.4	781.3	720.1
133	282.5	305.6	673.8	618.9
115	240.0	268.1	580.0	532.6
97	205.0	231.3	490.0	448.0
79	167.5	193.7	397.5	363.4
59	125.0	150.6	297.5	268.2
18	40.0	29.9	90.0	86.3
15	27.5	14.8	76.3	72.0

These results are plotted in Figure 7 and Figure 8. The strains for gage SG1 were offset downward by 50 μS for the figure and as shown in the table. This was a very small offset value and was a reasonable approach to correcting strain gage results that can show a zero offset. The predicted strain for location SG3 tended to diverge slightly from the measured strains at the higher loads. The knuckle tested was not the knuckle sectioned to obtain the core dimensions, so there could be differences in the geometry even though the knuckles were from the same batch cast by the manufacturer. The technicians who conducted the knuckle scanning commented that every knuckle they scanned had a slightly different core shape. The different core shape resulted in different load paths and stresses between knuckles.

The research team concluded from these two figures that the results of the FE model were a reasonable representation of the stresses of the physical knuckle under load.

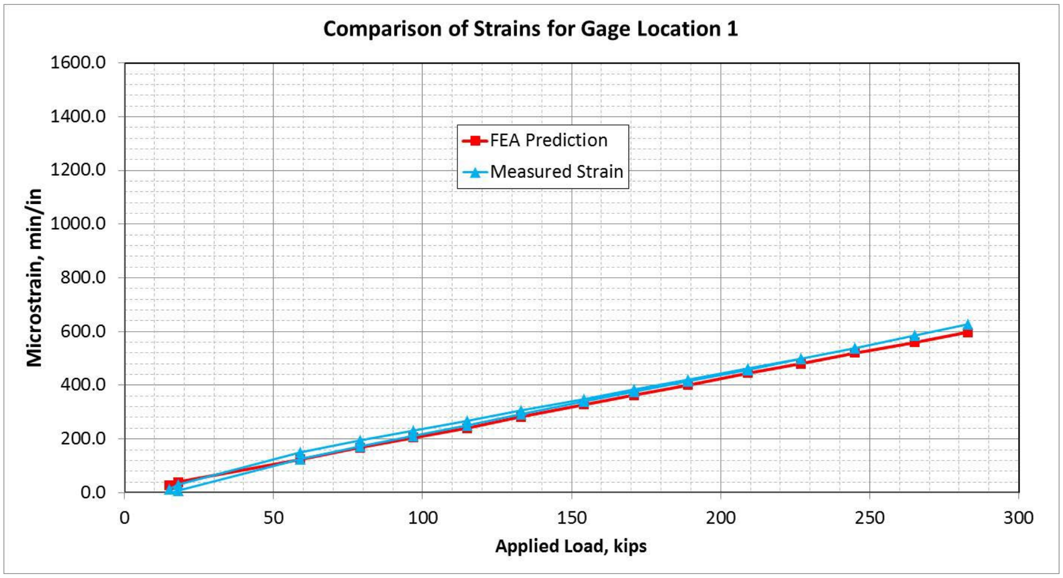

Figure 7. Comparison of measured and predicted strains at SG1

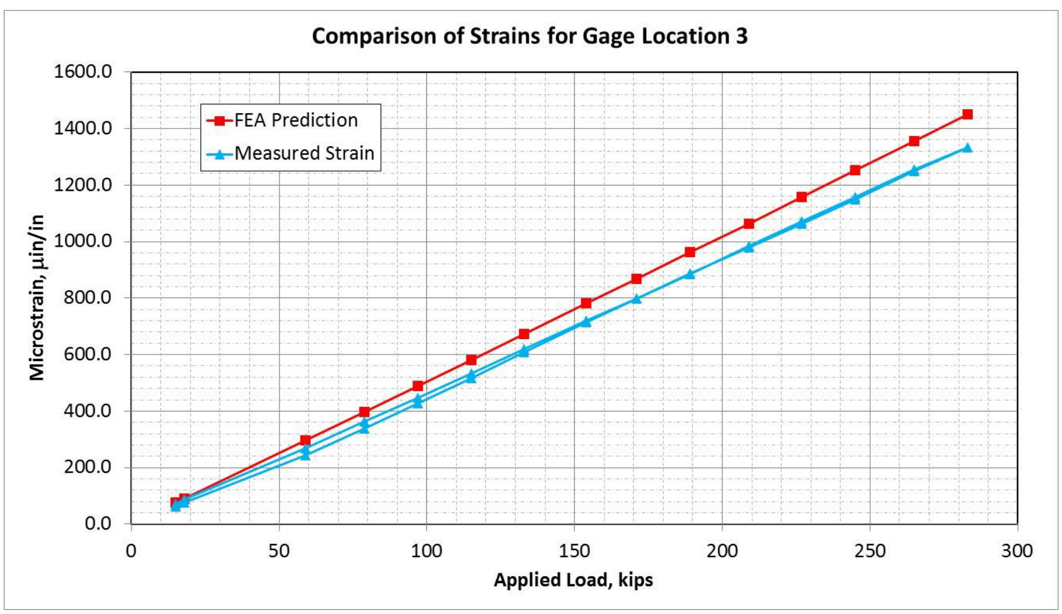

Figure 8. Comparison of measured and predicted strains at SG3

4 Failure Modes Evaluation

The AAR fatigue testing specified in the M-216 standard is typically applied with full-face contact between the two knuckles in the mated coupler pair in the test fixture. Loads higher than the largest load specified in the standard can occur in practice, either due to train handling, terrain, or both. While these loads do not necessarily occur often, they do have an effect on knuckle fatigue life. Loads can also be great enough to cause localized permanent deformation in the most highly stressed areas of the knuckle. Finally, connections within a train may be between loaded and empty cars, resulting in an offset load that further decreases knuckle fatigue life.

4.1 Fatigue Life Calculation

There are three major fatigue life prediction methods used in design and analysis: the stress life method, the strain life method, and the linear-elastic fracture mechanics method. These methods predict the number of cycles to failure for specific levels of loading. The stress-life method, the most traditional method that is used in AAR's MSRP-C-II-Chapter 7, Fatigue Design of New Freight Cars, is the easiest to implement and represents high-cycle applications adequately. This method, together with the Modified Goodman equation, was used for this analysis. In this method, the calculated elastic stress range is used with an S-N curve (i.e., a log-log graph of stress range versus number of cycles to failure) to determine the damage per stress range. This damage is accumulated throughout the operational history to determine the total damage. Since an S-N curve for the tested knuckle was not available, an S-N curve of 4135 cast steel normalized and tempered was used after adjustment to the appropriate material tensile strength. The tensile strength for 4135 cast steel is 112.7 ksi (777 Mpa); see Figure 9 [7]. This S-N curve was used as a baseline for constructing S-N curves for the tensile strength of the knuckle determined by hardness testing, and for the maximum-minimum tensile strengths defined for the knuckle steel.

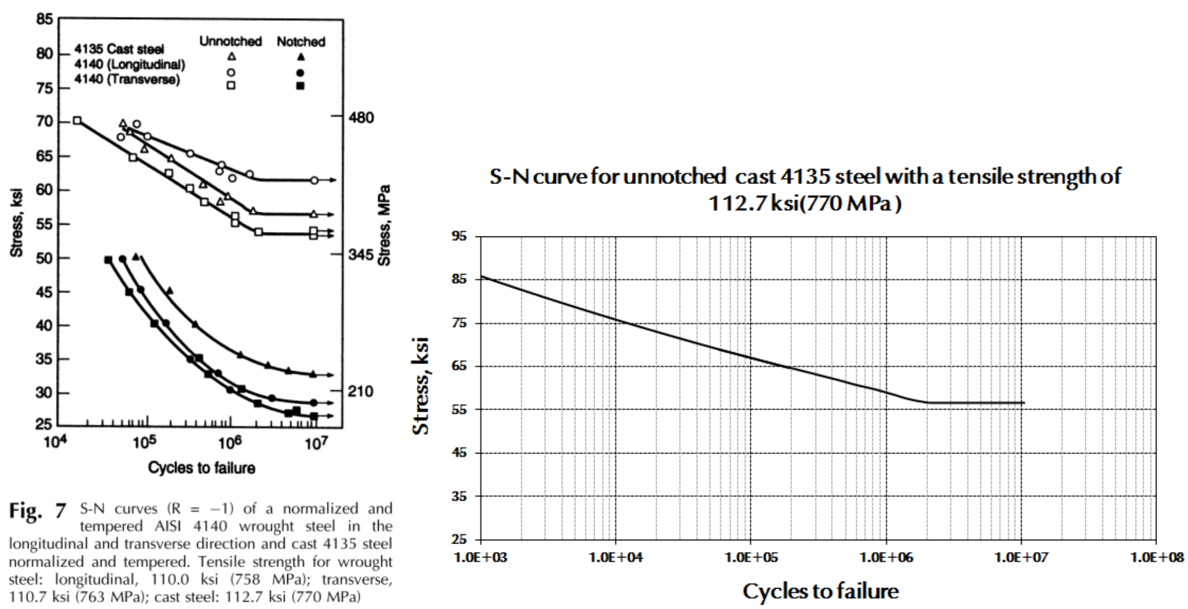

Figure 9. S-N curve for un-notched cast 4135 steel

Numerous tests have established that ferrous materials have an endurance limit defined as the highest level of alternating stress that can be withstood indefinitely by a test specimen without failure. The symbol for the endurance limit is S_e. For steel the following relationship can be used as a reliable assumption [6]:

$$S_e = 0.5\ S_u,\ \text{for}\ S_u < 200\ \text{ksi}$$

where S_u is the ultimate strength in tension (tensile strength) [7]. Based on this assumption and the S-N curve of un-notched cast 4135 steel, new S-N curves were developed for ultimate strengths of:

- 120 ksi, the minimum ultimate strength specified in the AAR manual
- 125 ksi, the minimum ultimate strength for this knuckle to survive the 600,000 total cycles specified in M-216 (the determination of this tensile strength is shown later)
- 138 ksi, the ultimate strength of the knuckle specimen obtained from Brinell hardness testing
- 150 ksi, the maximum ultimate strength specified in the AAR manual

Using the loading spectrum described in M-216 (Table 8), all stress values remain below the yield limit in the elastic regime. This allows for the use of a modified Goodman diagram to calculate the potential fatigue life of the knuckle. After corresponding stress values are obtained for each load cycle in the spectrum, the modified Goodman equation is used to obtain an equivalent alternating stress from the alternating stress (S_a), the mean stress (S_m), and the ultimate strength S_u. S-N curve data of the 4135 cast steel is then used to calculate the life for each stress cycle. Then Miner's rule is used to accumulate the total fatigue damage and the subsequent fatigue life in total cycles.

$$\frac{S_a}{S_{nf}} + \frac{S_m}{S_u} = 1\ ;\ (Modified\ Goodman\ Equation)$$

where:

- S_a is the amplitude of the alternating applied stress (i.e., half of the peak-to-peak stress)
- S_{nf} is alternating stress limit from the modified Goodman diagram for the applied alternating stress and mean stress
- S_m is the mean applied stress
- S_u is the ultimate (tensile) strength

Solving for S_{nf}, the equation becomes:

$$S_{nf} = \frac{S_a}{1 - \frac{S_m}{S_u}}$$

Table 8. Knuckle fatigue test load cycles from AAR M-216

Segment	Number of Cycles (Sinusoidal Form)	Total Elapsed Cycles	Cycle Load Range (Min to Max)[a/]
1	4	4	18–283 kips
2	2	6	18–265 kips
3	7	13	18–245 kips
4	10	23	18–227 kips
5	31	54	18–209 kips
6	77	131	18–189 kips
7	65	196	18–171 kips
8	73	269	18–154 kips
9	89	358	17–133 kips
10	105	463	17–115 kips
11	129	592	17–97 kips
12	187	779	17–79 kips
13	279	1058	15–59 kips

[a/] ±5% margin of error on minimum loads
±2% margin of error on maximum loads

The equivalent Goodman stress was calculated for each of the four ultimate strength values of 120 ksi, 125 ksi, 138 ksi, and 150 ksi (see Figure 10). The average von Mises stress was evaluated at the center of the highest stress area for each load segment.

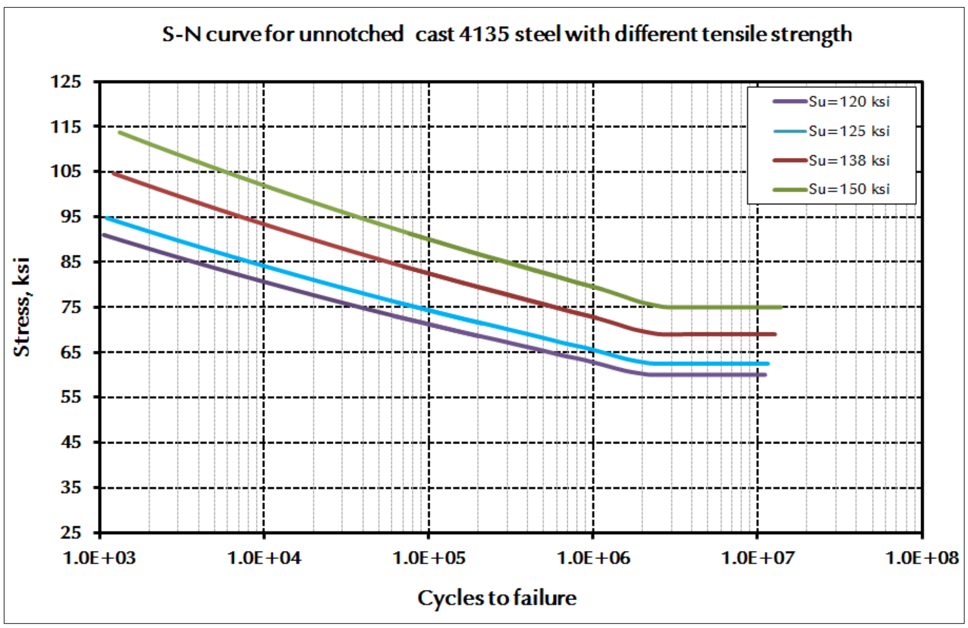

Figure 10. S-N curves for un-notched cast 4135 steel with different tensile strengths

4.2 Full-Face Contact Loading Fatigue Life Estimation

The results of the fatigue life estimation for full-face contact on the knuckle are shown in Table 9 through Table 12. The knuckle did not meet the AAR fatigue requirements at the minimum tensile strength of the cast steel material, as shown in Table 9. Fatigue life cycle estimation changed exponentially with alternating stress. The first few load segments specified in AAR M-216 resulted in very high alternating stresses and the modified Goodman diagram estimates significant fatigue life difference as a result of changing UTS. The total number of cycles changed drastically with the change in UTS. For example, increasing UTS from 120 ksi to 125 ksi resulted in fatigue life estimates which were four time higher.

Table 9. Fatigue life (S-N method) for S_u=120 ksi, draft load case #1, Region 1

Segment	S_m (ksi)	S_a(ksi)	S_{nf} (Su=120ksi)	N_f (120ksi)	Number of Cycles (n)	n/N_f
1	53.66	46.31	83.75	4957	4	0.000807
2	53.59	46.24	83.54	5199	2	0.000385
3	52.60	45.25	80.55	10208	7	0.000686
4	49.99	42.64	73.07	61995	10	0.000161
5	46.35	39.00	63.54	824364	31	3.76E-05
6	42.27	34.92	53.91	17316400	77	4.45E-06
7	38.60	31.25	46.06	3.19E+08	65	2.04E-07
8	35.13	27.78	39.27	6.12E+09	73	1.19E-08
9	30.64	23.70	31.82	3.01E+11	89	2.95E-10
10	26.96	20.02	25.82	1.44E+13	105	7.29E-12
11	23.29	16.35	20.28	1.26E+15	129	1.02E-13
12	19.61	12.67	15.14	2.82E+17	187	6.64E-16
13	15.12	8.99	10.28	3.68E+20	279	7.58E-19
Total number of cycles			**508,430**	**N/A**	$\Sigma(n_i/N_{fi})$=	**0.002081**

Table 10. Fatigue life (S-N method) for S_u=125 ksi, draft load case #1, Region 1

Segment	S_m (ksi)	S_a(ksi)	S_{nf} (S_u=125ksi)	N_f (125ksi)	Number of Cycles (n)	n/N_f
1	53.66	46.31	81.13	1.965E+04	4	0.000204
2	53.59	46.24	80.93	2.057E+04	2	0.000097
3	52.60	45.25	78.11	3.964E+04	7	0.000177
4	49.99	42.64	71.04	2.295E+05	10	0.000044
5	46.35	39.00	61.98	2.871E+06	31	1.08E-05
6	42.27	34.92	52.76	5.669E+07	77	1.36E-06
7	38.60	31.25	45.20	9.940E+08	65	6.54E-08
8	35.13	27.78	38.63	1.823E+10	73	4.00E-09
9	30.64	23.70	31.39	8.524E+11	89	1.04E-10
10	26.96	20.02	25.53	3.920E+13	105	2.68E-12
11	23.29	16.35	20.09	3.314E+15	129	3.89E-14
12	19.61	12.67	15.03	7.147E+17	187	2.62E-16
13	15.12	8.99	10.22	8.997E+20	279	3.10E-19
Total number of cycles			**1,984,202**	**N/A**	Σ(ni/Nfi)=	**0.000533**

Table 11. Fatigue life (S-N method) for S_u=138 ksi, draft load case #1, Region 1

Segment	S_m (ksi)	S_a(ksi)	S_{nf} (S_u=138ksi)	N_f (138ksi)	Number of Cycles (n)	n/N_f
1	53.66	46.31	75.76	4.815E+05	4	0.000008
2	53.59	46.24	75.58	5.028E+05	2	0.000004
3	52.60	45.25	73.11	9.317E+05	7	0.000008
4	49.99	42.64	66.85	4.889E+06	10	0.000002
5	46.35	39.00	58.72	5.388E+07	31	5.75E-07
6	42.27	34.92	50.34	9.341E+08	77	8.24E-08
7	38.60	31.25	43.38	1.471E+10	65	4.42E-09
8	35.13	27.78	37.26	2.457E+11	73	2.97E-10
9	30.64	23.70	30.46	1.027E+13	89	8.66E-12
10	26.96	20.02	24.88	4.343E+14	105	2.42E-13
11	23.29	16.35	19.66	3.395E+16	129	3.80E-15
12	19.61	12.67	14.77	6.803E+18	187	2.75E-17
13	15.12	8.99	10.09	7.879E+21	279	3.54E-20
Total number of cycles			**47,007,794**	**N/A**	Σ(ni/Nfi)=	**0.0000023**

Table 12. Fatigue life (S-N method) for S_u=150 ksi, draft load case #1, Region 1

Segment	S_m (ksi)	S_a(ksi)	S_{nf} (S_u=150ksi)	N_f (150ksi)	Number of Cycles (n)	n/N_f
1	53.66	46.31	72.09	6.148E+06	4	0.000001
2	53.59	46.24	71.93	6.408E+06	2	0.000000
3	52.60	45.25	69.68	1.156E+07	7	0.000001
4	49.99	42.64	63.94	5.669E+07	10	0.000000
5	46.35	39.00	56.44	5.719E+08	31	5.42E-08
6	42.27	34.92	48.62	9.047E+09	77	8.51E-09
7	38.60	31.25	42.07	1.320E+11	65	4.92E-10
8	35.13	27.78	36.27	2.061E+12	73	3.54E-11
9	30.64	23.70	29.78	7.947E+13	89	1.12E-12
10	26.96	20.02	24.41	3.159E+15	105	3.32E-14
11	23.29	16.35	19.35	2.330E+17	129	5.54E-16
12	19.61	12.67	14.58	4.421E+19	187	4.23E-18
13	15.12	8.99	9.99	4.810E+22	279	5.80E-21
Total number of cycles			585,213,546	**N/A**	Σ(ni/Nfi)=	**0.000002**

4.3 Loading Offset 3 Inches on Knuckle Face

Offsetting the loading upward by 3 inches on the knuckle face simulated the knuckle on a fully loaded car coupled to an empty car, because the truck suspension springs deflect different amounts at different loads. Nominally, the coupler heights were to be similar at an inter-car connection. Fatigue analysis for this situation on the most heavily stressed location on the knuckle for draft loading resulted in the fatigue life shown in Table 13. The expected number of cycles before failure was only 21,914 compared to 508,430 cycles for the knuckle in full-face height contact for all cycles, shown in Table 9. This was for the minimum tensile strength of 120 ksi for Grade E steel [5].

The analysis was also conducted for the knuckle with a loading offset 3 inches downward, as shown in Table 14. This simulated the knuckle on an empty car coupled to a fully loaded car. The knuckle fatigue life for this scenario was slightly greater than when the loading was offset 3 inches upward at 28,173 cycles. The number of cycles was different between the upward and downward contact patch shift because the knuckle geometry was not symmetric about the horizontal plane. Clearly, any one knuckle would not be operated exclusively in either state. However, empty/loaded car combinations are operated, sometimes for an entire train route. The next section discusses the methodology for combining the fatigue life calculations for all three scenarios (full-face contact, load shifted 3 inches upward, load shifted 3 inches downward).

Table 13. Fatigue life calculations for knuckle loading offset 3 inches upward

Segment	S_m (ksi)	S_a(ksi)	S_{nf} (Su=120ksi)	N_f (120ksi)	Number of Cycles (n)	n/N_f
1	58.42	43.15	84.09	4.606E+03	4	0.000868
2	58.24	42.97	83.49	5.253E+03	2	0.000381
3	58.08	42.81	82.97	5.906E+03	7	0.001185
4	57.97	42.7	82.61	6.401E+03	10	0.001562
5	57.89	42.62	82.34	6.787E+03	31	4.57E-03
6	57.78	42.51	81.99	7.357E+03	77	1.05E-02
7	57.7	42.43	81.73	7.801E+03	65	8.33E-03
8	57.64	42.37	81.53	8.153E+03	73	8.95E-03
9	57.02	42.6	81.17	8.858E+03	89	1.00E-02
10	54.53	40.11	73.52	5.541E+04	105	1.90E-03
11	48.36	33.94	56.85	6.475E+06	129	1.99E-05
12	40.78	26.36	39.93	4.496E+09	187	4.16E-08
13	31.38	18.65	25.25	2.174E+13	279	1.28E-11
Total number of cycles			**21,914**	**N/A**	$\Sigma(n_i/N_{fi})$=	**0.048280**

Table 14. Fatigue life calculations for knuckle loading offset 3 inches downward

Segment	S_m (ksi)	S_a(ksi)	S_{nf} (Su=120ksi)	N_f (120ksi)	Number of Cycles (n)	n/N_f
1	56.59	44.05	83.36	5.406E+03	4	0.000740
2	56.50	43.96	83.06	5.784E+03	2	0.000346
3	56.39	43.85	82.72	6.234E+03	7	0.001123
4	56.35	43.81	82.58	6.438E+03	10	0.001553
5	56.29	43.75	82.40	6.695E+03	31	4.63E-03
6	56.24	43.70	82.23	6.964E+03	77	1.11E-02
7	56.19	43.65	82.09	7.191E+03	65	9.04E-03
8	55.94	43.40	81.28	8.630E+03	73	8.46E-03
9	51.58	39.74	69.69	1.493E+05	89	5.96E-04
10	45.89	34.05	55.13	1.142E+07	105	9.19E-06
11	39.95	28.11	42.14	1.658E+09	129	7.78E-08
12	33.72	21.88	30.43	6.879E+11	187	2.72E-10
13	25.81	15.37	19.58	2.417E+15	279	1.15E-13
Total number of cycles			**28,173**	**N/A**	$\Sigma(n_i/N_{fi})$=	**0.037553**

4.4 Combining Offset Loading Conditions

The procedure for combining different loading conditions was defined in [1]. To obtain the fatigue life for different combinations of loading conditions, the n/N_f factor for each load i is combined:

$$\left(\frac{n}{N_f}\right)_{i,total} = \sum\left[\left(R_{aligned}\ \frac{n}{N_{f,i,aligned}}\right) + \left(R_{downward}\ \frac{n}{N_{f,i,downward}}\right) + \left(R_{upward}\ \frac{n}{N_{f,i,upward}}\right)\right]$$

where:

- $R_{aligned}$ is the fraction of the time the couplers are aligned vertically
- $R_{downward}$ is the fraction of the time the coupler is shifted downward
- R_{upward} is the fraction of the time the coupler is shifted upward
- n is the number of cycles for a particular loading cycle from M-216
- N_f is the number of cycles to failure for the loading cycle at this particular material strength

The R-factors must satisfy the equation:

$$R_{aligned} + R_{downward} + R_{upward} = 1$$

which is simply the condition that the knuckle operates 100 percent of the time in one of these three states.

These factors are used to calculate the fatigue life as shown in the following equation:

$$Cycles = 1{,}058 \frac{1}{\sum \frac{n_i}{N_{fi}}}$$

where 1,058 is the total number of cycles in the fatigue spectrum given in AAR M-216 for knuckle fatigue testing (Table 8). A knuckle with an estimated fatigue life of 600,000 cycles and higher (M-216, Para 4.5) is considered to satisfy the fatigue requirements.

Three critical areas were located during the effort, as shown in Figure 11. For full-face loading, Region 1 was the most highly stressed area.

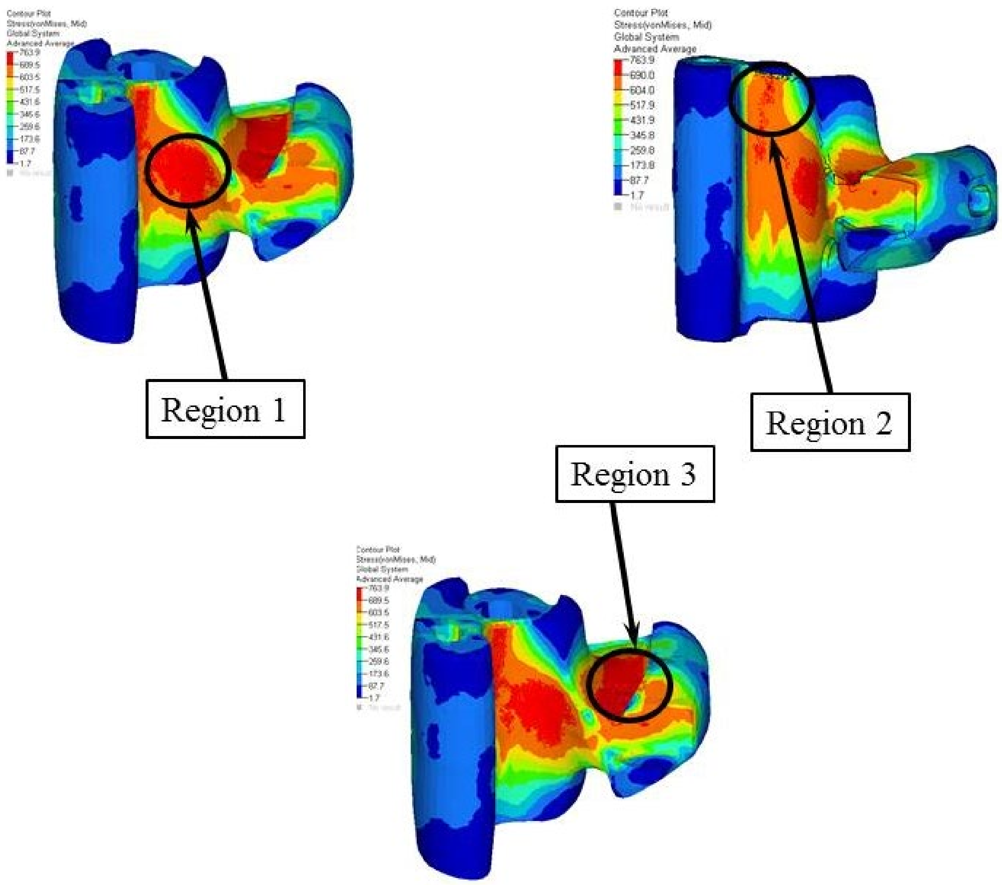

Figure 11. Three most highly stressed areas of knuckle

Various combinations of offset loads were calculated for Region 1, with the results shown in Table 15. The team drew several conclusions from the data in this table:

1. The knuckle did not meet the AAR fatigue requirement at the minimum tensile strength for any load combination, including full-face contact only.
2. Increasing the minimum tensile strength to 125 ksi improved knuckle life considerably, with the knuckle satisfying the AAR fatigue requirement.

3. Including the offset loading decreased the fatigue life at all tensile strengths by a significant amount even when the offset loading represented a small fraction of the overall cycles.
4. Offsetting the knuckle loading upward reduced the fatigue life slightly more than the downward offset of the loading.

Table 15. Calculated fatigue life for selected combinations of loading conditions and knuckle tensile strengths at Region 1

Load combination	120 ksi (AAR minimum)	125 ksi	138 ksi (strength of sectioned knuckle from Phase I)	150 ksi (AAR maximum)
Full face contact for all cycles	**508,430**	1,984,202	47,007,794	585,213,546
95% full face contact, 5% contact shifted 3 inches downward	**480,981**	1,878,671	44,584,597	555,700,548
95% full face contact, 5% contact shifted 3 inches upward	**460,599**	1,799,655	42,739,293	532,970,454
95% full face contact, 2.5% upward and 2.5% downward	**470,569**	1,838,314	43,642,448	544,098,213
A life greater than 600,000 cycles satisfies the AAR fatigue requirement.				

An alternative method for comparing the fatigue lives of the various tensile strength knuckles is to calculate the ratio of the predicted number of cycles and the required number of cycles. Any result greater than or equal to 1 satisfies the AAR fatigue requirement. This alternative parameter is shown in Table 16 for Region 1 for the same load combinations and tensile strengths as shown above in Table 15.

Table 16. Calculated fatigue life ratios for selected combinations of loading conditions and knuckle tensile strengths at Region 1

Load combination	120 ksi (AAR minimum)	125 ksi	138 ksi (strength of sectioned knuckle from Phase I)	150 ksi (AAR maximum)
Full face contact for all cycles	**0.85**	3.31	78.35	975.36
95% full face contact, 5% contact shifted 3 inches downward	**0.80**	3.13	74.31	926.17
95% full face contact, 5% contact shifted 3 inches upward	**0.77**	3.00	71.23	888.28
95% full face contact, 2.5% upward and 2.5% downward	**0.78**	3.06	72.74	906.83
A result greater than 1.0 satisfies the AAR fatigue requirement.				

The same combinations of offset loads were calculated for Region 2, with the results shown in Table 17. There were several conclusions drawn from the data in this table:

1. None of the loading combinations considered resulted in this region failing to achieve the AAR minimum number of cycles.

2. Increasing the minimum tensile strength to 125 ksi improved the knuckle life considerably, with the knuckle satisfying the AAR fatigue requirement.
3. Including the offset loading decreased the fatigue life at all tensile strengths by a significant amount even when the offset loading represented a small fraction of the overall cycles.
4. Offsetting the knuckle loading upward reduced the fatigue life slightly more than the downward offset of the loading.

Again, the fatigue life ratios for Region 2 are shown in Table 18.

Table 17. Calculated fatigue life for selected combinations of loading conditions and knuckle tensile strengths at Region 2

Load combination	120 ksi (AAR minimum)	125 ksi	138 ksi (strength of sectioned knuckle from Phase I)	150 ksi (AAR maximum)
Full face contact for all cycles	902,553	3,484,466	80,690,449	988,430,221
95% full face contact, 5% contact shifted 3 inches downward	791,666	3,066,094	71,463,054	879,266,783
95% full face contact, 5% contact shifted 3 inches upward	840,540	3,251,678	75,614,720	928,904,480
95% full face contact, 2.5% upward and 2.5% downward	815,372	3,156,160	73,480,291	903,404,307
A life greater than 600,000 cycles satisfies the AAR fatigue requirement.				

Table 18. Calculated fatigue life ratios for selected combinations of loading conditions and knuckle tensile strengths at Region 2

Load combination	120 ksi (AAR minimum)	125 ksi	138 ksi (strength of sectioned knuckle from Phase I)	150 ksi (AAR maximum)
Full face contact for all cycles	1.50	5.81	134.48	1,647.38
95% full face contact, 5% contact shifted 3 inches downward	1.32	5.11	119.11	1,465.44
95% full face contact, 5% contact shifted 3 inches upward	1.40	5.42	126.02	1,548.17
95% full face contact, 2.5% upward and 2.5% downward	1.36	5.26	122.47	1,505.67
A result greater than 1.0 satisfies the AAR fatigue requirement.				

The same combinations of offset loads were calculated for Region 3, with the results shown in Table 19. There were several conclusions drawn from the data in this table:

1. When the load was shifted up or down, the most highly stressed area became Region 3. This was due to the geometrical asymmetry of the knuckle in both the vertical and lateral planes.
2. Increasing the minimum tensile strength to 125 ksi improved the knuckle life considerably, with the knuckle satisfying the AAR fatigue requirement.
3. Including the offset loading decreased the fatigue life at all tensile strengths by a significant amount even when the offset loading represented a small fraction of the overall cycles.
4. Offsetting the knuckle loading upward reduced the fatigue life slightly more than the downward offset of the loading.

Further analysis showed that operating with the load shifted upward only 13 percent of the time resulted in the 125-ksi tensile strength knuckle not meeting the AAR fatigue life requirement.

Table 19. Calculated fatigue life for selected combinations of loading conditions and knuckle tensile strengths at Region 3

Load combination	120 ksi (AAR minimum)	125 ksi	138 ksi (strength of sectioned knuckle from Phase I)	150 ksi (AAR maximum)
Full face contact for all cycles	702,892	2,728,708	63,820,530	786,253,069
95% full face contact, 5% contact shifted 3 inches downward	**319,869**	1,291,595	32,674,910	424,041,946
95% full face contact, 5% contact shifted 3 inches upward	**275,239**	1,136,510	29,975,631	398,972,311
95% full face contact, 2.5% upward and 2.5% downward	**295,880**	1,209,100	31,267,121	411,125,309
A life greater than 600,000 cycles satisfies the AAR fatigue requirement.				

Table 20. Calculated fatigue life ratios for selected combinations of loading conditions and knuckle tensile strengths at Region 3

Load combination	120 ksi (AAR minimum)	125 ksi	138 ksi (strength of sectioned knuckle from Phase I)	150 ksi (AAR maximum)
Full face contact for all cycles	1.17	4.55	106.37	1,310.42
95% full face contact, 5% contact shifted 3 inches downward	**0.53**	2.15	54.46	706.74
95% full face contact, 5% contact shifted 3 inches upward	**0.46**	1.89	49.96	664.95
95% full face contact, 2.5% upward and 2.5% downward	**0.49**	2.02	52.11	685.21
A result greater than 1.0 satisfies the AAR fatigue requirement.				

The effect of different fractions of offset loading combined with the full-face contact case on knuckle fatigue life is shown in Figure 12, assuming 120-ksi tensile strength knuckles. All the results were lower than the AAR-required minimum cycle counts. When the tensile strength was increased to 125 ksi, all of the loading combinations satisfied the AAR minimum number of cycles, as shown in Figure 13.

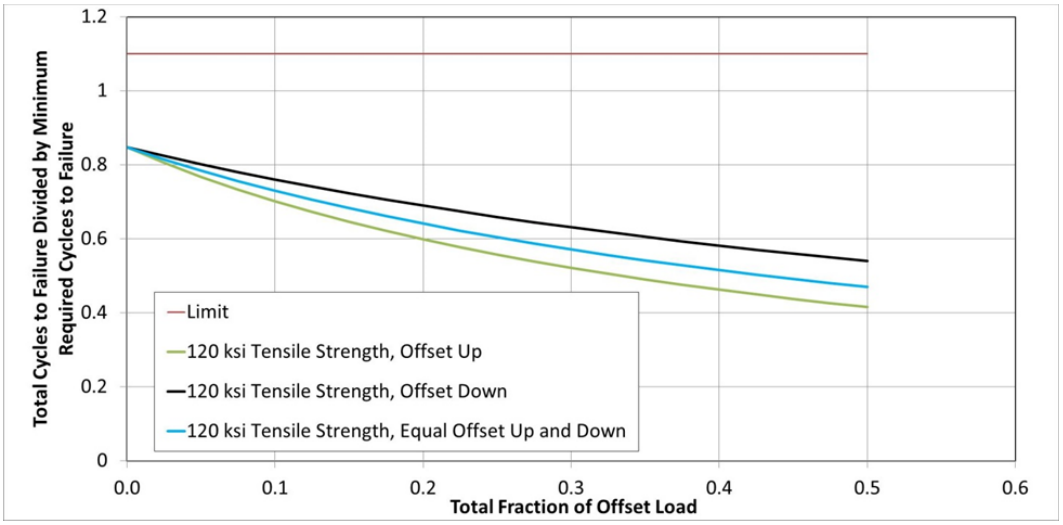

Figure 12. Effect of increased loading cycles on overall fatigue life of knuckle, 120-ksi tensile strength

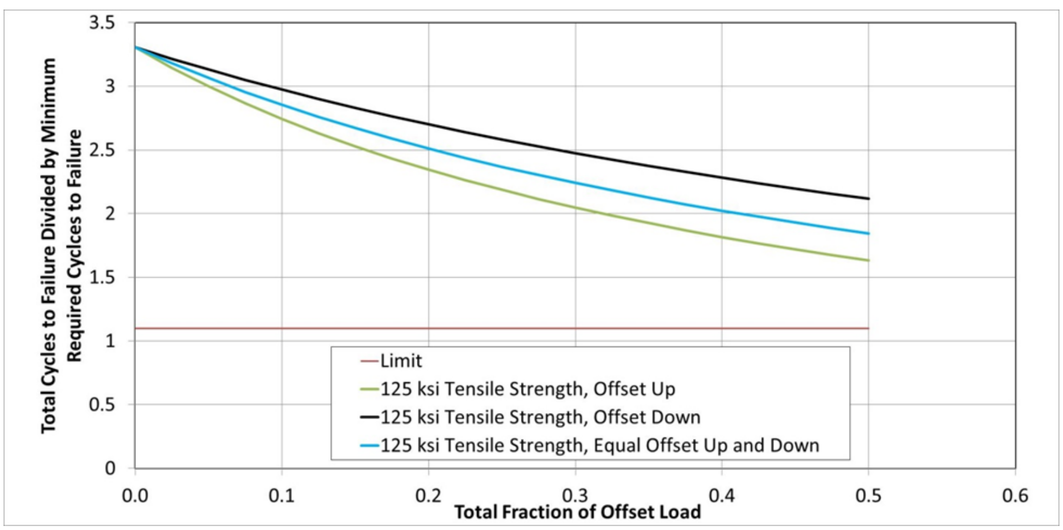

Figure 13. Effect of increased loading cycles on overall fatigue life of knuckle, 125-ksi tensile strength

4.5 Increased Loading Analysis

The maximum load included in the AAR fatigue spectrum was 283 kips draft. However, higher loads can occasionally occur in the field due to slack action. The team analyzed the effect of increased draft loads on the knuckle to determine the peak stresses. The higher draft loads included in the analysis are shown in Table 21.

Table 21. Increased draft loads included in fatigue analysis

Higher Draft Loads Included (kips)
300
325
350
375
400

The research team found that localized yielding occurred in the knuckle even at a 283-kips load in the 120-ksi strength material. The number of nodes experiencing plastic strain increased as the load increased, as shown in Figure 14, where the number in the ovals to the right of the curves is the maximum percentage of plastically deformed elements at that load. Even at the maximum load specified in the AAR fatigue spectrum, the plastic knuckle deformation occurred over almost 10 percent of the knuckle. However, most of the nodes plastically deformed only a slight amount. For comparison, the maximum elastic strain before the material entered the plastic region was 0.15 in/in; the maximum plastic strain was only 0.028 in/in. The maximum plastic strain for the 283-kip load was much less, at 0.015 in/in. Note that only a very few nodes were subjected to the peak strain, as all of the curves shown in Figure 14 flattened out before 0.003 in/in strain.

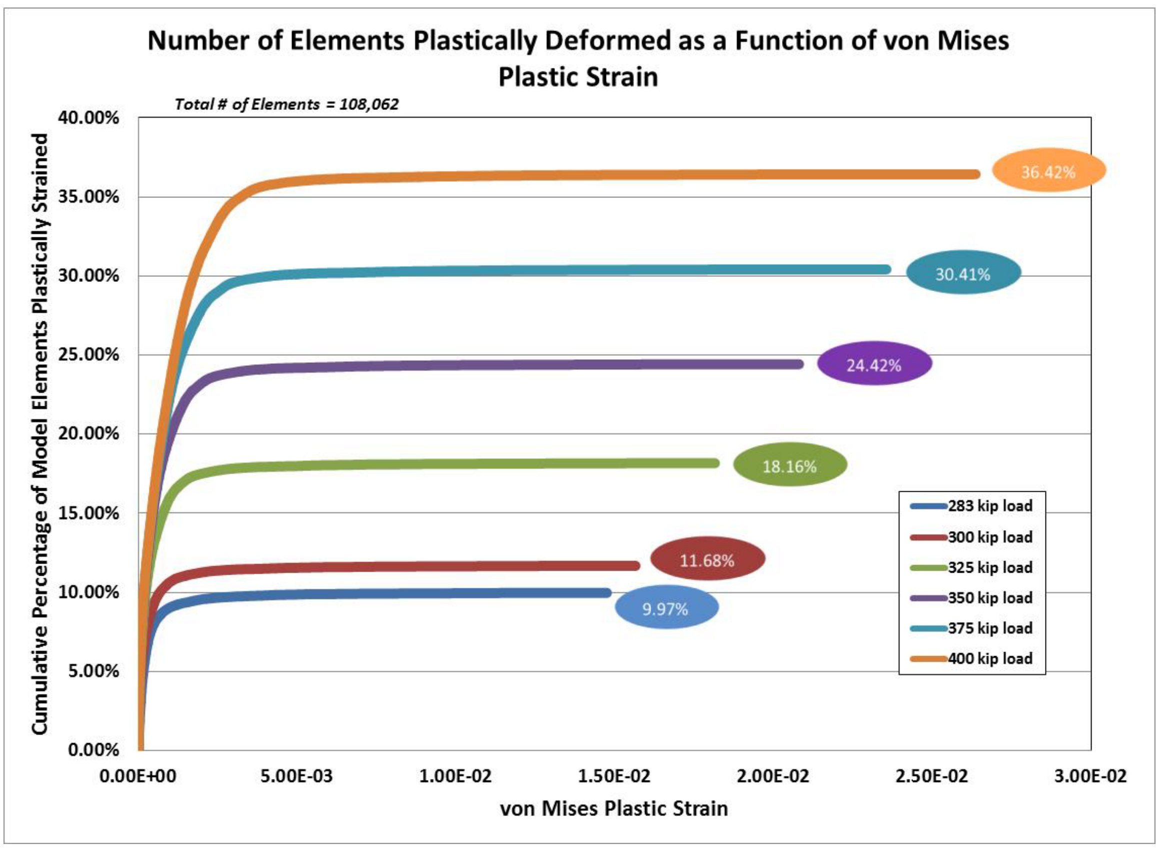

Figure 14. Plastic strain on knuckle at increasing draft load

Plastic strain hardened the knuckle at the deformed locations and a residual tensile stress was left in the material after the load had been removed. The effect of the residual stress was to reduce the fatigue life by increasing the mean stress at the locations which had been deformed. The effect of increasing the mean stress was to shift the stress amplitude further right on the sloped portion of the stress-strain curve, where fewer cycles were required to exceed the failure criterion.

The team then included cycles of the increased loading in its fatigue analysis load spectrum. The results of including just one fatigue cycle, moving from the lowest loading to each of the new highest loadings, are shown in Table 22 for both the 120- and 125-ksi tensile strength materials.

Table 22. Fatigue life for knuckle having 120-ksi tensile strength with one cycle of heavier loading included in spectrum, for full-face contact

Case	Fatigue Life, Cycles, 120 ksi Tensile Strength	Fatigue Life, Cycles, 125 ksi Tensile Strength
Baseline M-216	**508,430**	1,984,202
M-216 plus 18 to 300 kip cycle	**463,506**	1,811,399
M-216 plus 18 to 325 kip cycle	**462,419**	1,807,330
M-216 plus 18 to 350 kip cycle	**461,126**	1,802,497
M-216 plus 18 to 375 kip cycle	**459,613**	1,796,847
M-216 plus 18 to 400 kip cycle	**457,672**	1,789,601
M-216 plus one cycle of all five heavier loadings	**335,778**	1,318,259
A life greater than 600,000 cycles satisfies the AAR fatigue requirement.		

The fatigue life dropped significantly with only one extra load cycle including only one load greater than the peak load in the AAR spectrum. For example, adding one cycle of 18 to 350 kip loading (a 0.09 percent increase in the number of cycles) dropped the fatigue life by nearly 47,000 cycles, or 9.3 percent of the original fatigue life. The inclusion of at least one of these load cycles into the AAR M-216 fatigue life testing requirement may be appropriate, especially since longer and heavier trains are now being operated. The fatigue life of the 125-ksi tensile strength knuckle was much greater, at 1,318,259 cycles, even when including one cycle of all 5 heavier loadings into the loading spectrum. Thus, increasing the material minimum tensile strength by only 5 ksi caused this knuckle geometry to pass the AAR fatigue requirement, whereas the current minimum of 120 ksi failed with only a little more than half of the required cycles completed. Therefore, increasing the minimum tensile strength requirement by only 5 ksi can result in a significant increase in knuckle fatigue life.

5 Knuckle Design Enhancement

There are many factors involved in knuckle design, including:

1. The knuckle must match the exterior geometry to allow coupling and uncoupling to occur to satisfy interchange requirements.
2. The knuckle must be able to carry the required longitudinal loads for train operation, both static and dynamic.
3. The knuckle must fail in tension before any other component in the train during draft operation, thus acting as the mechanical fuse.
4. The knuckle must be light enough to allow the train crew to carry a spare knuckle from the locomotive to the point of train separation for installation.

Knuckles are complex castings with core cooling rates throughout the casting designed to be as uniform as possible by minimizing differences in the casting thickness. More even cooling of a casting minimizes the potential for casting flaws and promotes the development of more uniform material properties throughout the casting. The core reduces the weight of the knuckle by creating voids in the knuckle interior and is therefore crucial in any knuckle design.

One possible design change to the knuckle geometry that meets the constraints listed above is to increase the thickness at the critical areas of the knuckle. This means reducing the size of the core at this section, instead of increasing the outer dimension. The material strength is another potential change that can be accomplished without needing to change the molds used to cast the knuckles.

5.1 Material Strength

AAR MSRP M-201 requires a minimum tensile strength of 120 ksi for knuckle cast steel (grade E). Improvement in knuckle material strength (e.g., an increase in UTS) is expected to change the fatigue life considerably under the assumptions of this study. For instance, increasing UTS from 120 to 125 ksi is estimated to result in four times longer fatigue life.

5.2 Geometry Enhancements

5.2.1 Solid Knuckle

To evaluate the maximum possible strength improvement from increasing section thickness, an analysis of the knuckle was conducted with the core removed, making the knuckle solid. This was the best possible condition in terms of geometric enhancement, since there was no possibility of any additional thickness increases, although the team recognized that this condition may not be physically realizable. This modification increased the weight of the knuckle from 86.6 to 109.3 lb, an increase of 26 percent. The fatigue life of the knuckle with this geometry change is shown in Table 23. The number of cycles the knuckle can sustain before failure with the minimum tensile strength increased by an order of magnitude compared to the number of cycles before failure for the original geometry. This suggests that a smaller thickness change in critical areas could reduce stresses significantly and improve the fatigue life.

Table 23. Fatigue life for solid knuckle

Case	Region 1 Life, Cycles	Region 2 Life, Cycles	Region 3 Life, Cycles
120 ksi tensile strength	3,049,156	43,540,184	23,969,464
125 ksi tensile strength	12,343,587	163,755,115	92,163,001
138 ksi tensile strength	257,251,098	2,930,651,188	1,722,543,750
150 ksi tensile strength	3,071,815,856	31,489,984,934	19,035,503,527
A life greater than 600,000 cycles satisfies the AAR fatigue requirement.			

The team also analyzed combining the point of load application for the solid knuckle, as shown in Table 24.

Table 24. Calculated fatigue life for selected combinations of loading conditions and knuckle tensile strengths at Region 1 for the solid knuckle

Load combination	120 ksi (AAR minimum)	125 ksi	138 ksi (strength of sectioned knuckle from Phase I)	150 ksi (AAR maximum)
Full face contact for all cycles	3,049,156	12,343,587	257,251,098	3,071,815,856
95% full face contact, 5% contact shifted 3 inches downward	2,710,608	11,020,355	231,618,282	2,780,961,754
95% full face contact, 5% contact shifted 3 inches upward	2,730,507	11,097,954	233,120,920	2,798,072,399
95% full face contact, 2.5% upward and 2.5% downward	2,720,521	11,059,018	232,367,172	2,789,490,837
A life greater than 600,000 cycles satisfies the AAR fatigue requirement.				

Table 25. Calculated fatigue life ratios for selected combinations of loading conditions and knuckle tensile strengths at Region 1 for the solid knuckle

Load combination	120 ksi (AAR minimum)	125 ksi	138 ksi (strength of sectioned knuckle from Phase I)	150 ksi (AAR maximum)
Full face contact for all cycles	5.08	20.57	428.75	5,119.69
95% full face contact, 5% contact shifted 3 inches downward	4.52	18.37	386.03	4,634.94
95% full face contact, 5% contact shifted 3 inches upward	4.55	18.50	388.53	4,663.45
95% full face contact, 2.5% upward and 2.5% downward	4.53	18.43	387.28	4,649.15
A result greater than 1.0 satisfies the AAR fatigue requirement.				

5.2.2 Knuckle with Smaller Core

The team next investigated the effect of thickening key areas of the knuckle to reduce stress and thereby improve fatigue life. Two dimensions were identified for modification, as shown in Figure 15. The dimensions for both the baseline and the modified model are shown in Table 26.

Table 26. Dimensions of core modified for knuckle enhancement

	Original Baseline Value, inch	Updated Value, inch
Dimension "t," thickness on inner face	1.30	1.50
Dimension "h," spacing between cores near flag hole	2.75	2.50

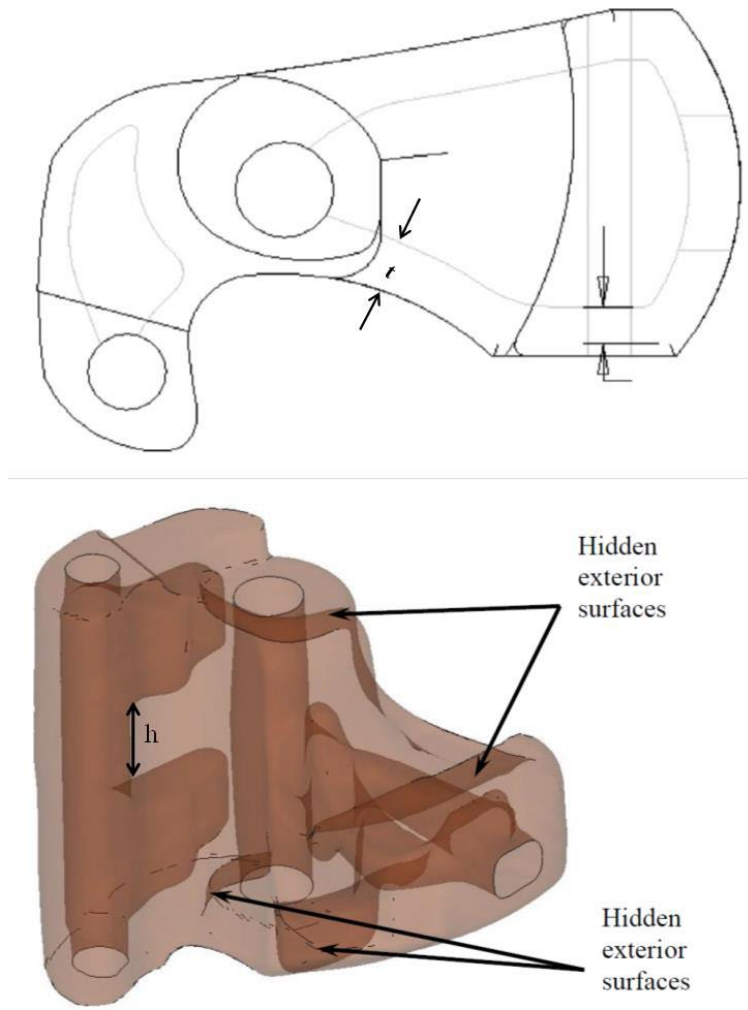

Figure 15. Areas of knuckle thickened in the FE model

The FE model results were then analyzed to obtain the knuckle fatigue life (see Table 27). The increased thickness in these two key areas improved the fatigue life so that a knuckle having only the AAR minimum tensile strength of 120 ksi now met the fatigue testing requirement of AAR MSRP M-216. The weight change was negligible for these thickness updates. The knuckle originally weighed 86.6 lb, while the updated model weighed 88.12 lb – an increase of 1.5 lb or 1.7 percent. Further design optimization could eliminate the weight increase.

Table 27. Fatigue life for knuckle with thickness changes in key areas, full-face contact of the connecting knuckle

Case	Region 1 Life, Cycles	Region 2 Life, Cycles	Region 3 Life, Cycles
120 ksi tensile strength	930,048	1,032,840	2,827,705
125 ksi tensile strength	3,615,366	3,987,077	10,768,758
138 ksi tensile strength	84,951,593	92,315,826	242,423,024
150 ksi tensile strength	1,051,510,467	1,130,761,154	2,911,763,013
A life greater than 600,000 cycles satisfies the AAR fatigue requirement.			

The fatigue life for the knuckle when considering selected loading combinations is shown in Table 28.

Table 28. Calculated fatigue life for selected combinations of loading conditions and knuckle tensile strengths at Region 1 with the thickness changes included

Load combination	120 ksi (AAR minimum)	125 ksi	138 ksi (strength of sectioned knuckle from Phase I)	150 ksi (AAR maximum)
Full face contact for all cycles	930,048	3,615,366	84,951,593	1,051,510,467
95% full face contact, 5% contact shifted 3 inches downward	875,518	3,406,171	80,171,065	993,495,699
95% full face contact, 5% contact shifted 3 inches upward	856,492	3,332,160	78,429,308	971,913,252
95% full face contact, 2.5% upward and 2.5% downward	865,900	3,368,759	79,290,623	982,585,975
A result greater than 600,000 cycles satisfies the AAR fatigue life requirement.				

The ratio of the predicted number of cycles and the required number of cycles is shown in Table 29. The knuckle having only the minimum tensile strength passed the fatigue requirement.

Table 29. Calculated fatigue life ratios for selected combinations of loading conditions and knuckle tensile strengths at Region 1 with the thickness changes included

Load combination	120 ksi (AAR minimum)	125 ksi	138 ksi (strength of sectioned knuckle from Phase I)	150 ksi (AAR maximum)
Full face contact for all cycles	1.55	6.03	141.59	1,752.52
95% full face contact, 5% contact shifted 3 inches downward	1.46	5.68	133.62	1,655.83
95% full face contact, 5% contact shifted 3 inches upward	1.43	5.55	130.72	1,619.86
95% full face contact, 2.5% upward and 2.5% downward	1.44	5.61	132.15	1,637.64
A result greater than 1.0 satisfies the AAR fatigue requirement.				

This result is shown graphically in Figure 16 when the as-built and enhanced-geometry knuckles were subjected to offset loading. The knuckle with enhanced geometry met the fatigue life requirement up to approximately 28 percent offset loading.

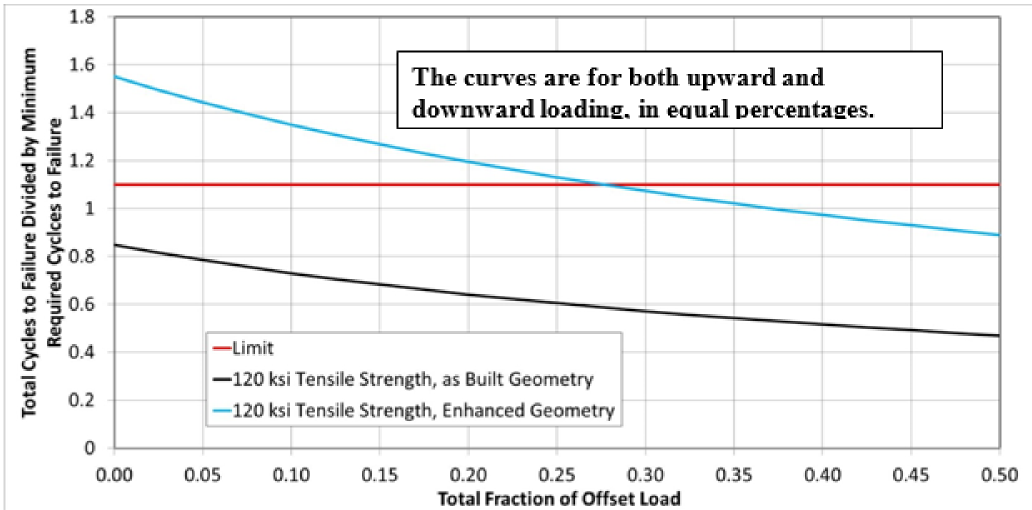

Figure 16. Effect of core dimensional changes on overall fatigue life of knuckle, 120-ksi tensile strength

5.2.3 Further Optimization

Tools for optimizing the knuckle to minimize the stresses currently exist and would be useful in determining the optimum dimensions for the knuckle. One of these tools is design of experiments (DOE), or experimental design.

DOE is a systematic method to determine the relationship among factors affecting a process and the output of that process. In this case, the process was the fatigue life. The factors to be included in an analysis of this type were:

- Material strength
- Thickness on inner face
- Spacing between cores near flag hole

A transfer function defining the fatigue life with changes in any of these three parameters was developed using FE simulation results for several permutations of values for these three parameters. This function was then used to optimize the values of the three parameters to maximize the fatigue life while satisfying any other conditions, such as maximum weight of the knuckle.

6 Conclusion and Recommendations

A sample coupler knuckle was modeled and subjected to simulated loading using AAR's fatigue loading spectrum, both in the original configuration and with some minor adjustments made to key geometry parameters. Several material strengths were also analyzed.

The knuckle loading was shifted both upward and downward to simulate an empty/loaded car connection and the difference in spring (i.e., suspension) deflections between an empty and loaded car, which can occur in revenue service. Researchers developed a methodology to combine the fatigue lives of the full-face contact and the shifted upward and downward contact.

The research team determined the original knuckle design using the minimum tensile strength required by AAR in M-201 [2] would not pass the fatigue requirements of AAR M-216 [5].

Other tensile strengths were included in the analysis, up to the AAR maximum of 150 ksi for Grade E steel. The team found:

1. Combining the full-face contact with either the upward or downward shift (offset loading) of the contact area decreased the fatigue life because the stresses in the critical areas increasd as the contact patch moved. The fatigue life decreased as the fraction of the offset loading increased.
2. The downward load shift increased the stress in the knuckle more than the upward load shift. Note that in any offset condition, both upward and downward shifts were experienced in a coupler connection because an upward loading shift occurred on the loaded car (i.e., the coupler horizontal centerline was below the coupler centerline of the empty car) and the downward loading shift occurred on the empty car.
3. Including only one cycle of a heavier draft load of 300 kips reduced the fatigue life significantly. Coupler loads greater than the 283-kip maximum specified in AAR M-216 fatigue spectrum occur in revenue service operation as listed in the Freight Equipment Environmental Sampling Test Program (FEEST) [6]. Consideration should be given to including a higher loading cycle in the M-216 standard.
4. Increasing the tensile strength minimum by only 5 ksi from the present 120 ksi would sufficiently improve the fatigue life so that the knuckle would pass the fatigue requirement both with full-face contact only and when 5 percent of the cycles are on the knuckle with the contact shifted upward 3 inches and 5 percent of the cycles are with the loading contact shifted downward 3 inches (i.e., full-face contact only 90 percent of the time).
5. Increasing the thickness on the inner face also improved the fatigue life so that the knuckle would pass the fatigue requirement even with the present minimum tensile strength of 120 ksi.

The easiest change to immediately improve knuckle fatigue life would be to increase the minimum tensile strength to at least 125 ksi.

The team recommends that design optimization based on a DOE approach be conducted on the knuckle using the tensile strength, thickness of the inner face, and spacing of the cores at the flag hole as fundamental design parameters. This method will help determine the optimum design parameter changes to achieve the highest knuckle fatigue life possible under the geometry and weight constraints.

7 References

1. American Association of Railroads (2014). *Knuckles, Types E and F – Fatigue Test*. MSRP M-216, Section S.
2. Altair HyperWorks. Version 13.0.
3. Ansys, Inc. Version 16.2.
4. American Association of Railroads (2014). *Castings, Steel*. MSRP M-201, Section S.
5. Stephens, R., Fatemi, A., & Fuchs, H. (2000). *Metal Fatigue in Engineering, 2nd Edition*. New York: John Willey & Sons.
6. ASM International (November 2009). *Casting Design and Performance*. Materials Park, Ohio.
7. American Association of Railroads (2013). *Design, Fabrication, and Construction of Freight Cars*. MSRP M-1001, Section C-II, Chapter 7: Fatigue Design.

Abbreviations and Acronyms

AAR	Association of American Railroads
ASTM	American Society of Testing and Materials
CAD	Computer Aided Design
DOE	Design of Experiments
DOT	Department of Transportation
FEA	Finite Element Analysis
FEEST	Freight Equipment Environmental Sampling Test Program
FRA	Federal Railroad Administration
kips	Kilo Pounds
ksi	Kilo Pound per Square Inch
MSRP	Manual of Standards and Recommended Practices