STRUCTURAL RESPONSE OF RAILROAD TANK CARS DURING ACOUSTIC EMISSION TESTING

by

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For my parents, Fayez and Ferial

& to all my teachers

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Abstract

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The successful use of Acoustic Emission Testing as a nondestructive testing technique for evaluating the structural integrity of railroad tank cars hinges on the ability to reach favorable stress levels in the areas where defects are located. This study investigated a general purpose car, a bar-reinforced car, and a pressure car under the influence of different loading stimuli. The cars were tested with the loads specified by the existing Association of American Railroads procedure for the acoustic emission inspection of railroad tank cars and with other loading methods. The tests conducted provide a technical basis for an alternative stressing procedure to be used in acoustic emission testing of railroad tank cars.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Every day for more than a century, railroad tank cars have been used to transport bulk liquids in the United States and Canada. It is estimated that over 210,000 tank cars operate in North America carrying materials ranging from food products, such as vinegar and corn syrup, to fuels, fertilizers, liquefied petroleum gas (LPG), and other industrial chemicals such as caustic soda, and anhydrous ammonia. A little more than half of the tank cars in service carry materials that have physical and chemical properties that are harmful if released (TRB 1994).

Most tank car designs are categorized as either belonging to a pressure or nonpressure car category. Nearly all pressure cars are used to carry materials that are classified as hazardous by the federal government. This is in contrast to only 40 percent of the nonpressure tank cars being used for shipping hazardous materials (TRB 1994). There are many common design features between pressure and nonpressure cars. They both have horizontal cylindrical shaped tanks capped with ellipsoidal or hemispheric shaped heads. Pressure and nonpressure car designs are also different in many important respects. Pressure cars have thicker walls and have their fittings better protected. These fittings are almost always mounted on top of the tank where they are less susceptible to damage. Most of the tank cars are constructed from steel, though some are made from stainless steel and alloys of aluminum or nickel.

Many advances have been made in the area of tank car design to protect the environment and the public from uncontrolled releases. Maintenance of an aging fleet of tank cars requires continued vigilance by the operators of these tank cars to ensure that undesirable flaws that may be present in the original construction or develop during service are detected well before they propagate and become critical. The tanks of many pressure and nonpressure cars are usually wrapped with insulating material and covered by a steel jacket. This is done to control product temperature variation during transport.

Access to the outside of the tank car for inspection requires a time consuming and expensive effort to remove the insulation and inspect the critical areas with Nondestructive Testing (NDT) techniques such as dye penetrant, magnetic particle or ultrasonics. Internal inspection requires cleanout and decontamination of the car and disposal of the waste products. The use of Acoustic Emission (AE) inspection techniques that can successfully inspect large areas of a railroad tank car with only a limited amount of access is potentially very beneficial to the railroad industry. AE inspection is also a quick and reliable inspection method of non-jacketed tank cars and compared to other methods has the advantage of being sensitive to structurally significant defects.

1.2 RESEARCH OBJECTIVES

The focus of this research was development and evaluation of new techniques of stressing railroad tank cars to increase the magnitude of the stresses and to make them more favorable for an acoustic emission test. The application of a tensile force to the couplers of a railroad tank car was one of the many stressing methods investigated.

The research reported in this thesis was carried out under the guidance of the Acoustic Emission Task Force of the Association of American Railroads (AAR). The procedure that will be developed is an alternative test to comply with the United States Department of Transportation (DOT) requirement set in CFR title 49, part 180.509 (Federal 1995). Results reported from this research will provide the technical basis for this procedure.

1.3 RESEARCH PROGRAM OVERVIEW

Three tank cars have been instrumented and subjected to a rigorous and extensive testing program. The tank cars selected were of different designs belonging to three major categories of tank car design. This made it possible to obtain a comprehensive picture of the structural response of most in-service tank cars subjected to different loadings.

The general purpose tank car represents the largest category of cars in service, followed by the pressure car. For a pressure car, the major departure in the design from a general purpose car is the larger wall thickness needed to handle contents at a much higher pressure. A bar-reinforced tank car was also selected as part of this program. The heavy longitudinal reinforcement on the bottom of this car is known to alter the behavior of the car to the loads specified by the AAR procedures for AE testing of railroad tank cars (AAR 1999).

Strain gauge, linear potentiometer and load data were used to understand the structural response of the railroad tank cars to different loads. A better understanding of the existing AAR procedures was the first direct result of the testing conducted. Great insight has been gained regarding the advantages and limitations of the existing AAR procedures. The tests conducted have revealed important differences in the behavior of empty and full tank cars.

The remainder of this thesis is organized into six chapters. Chapter 2 contains background information on the existing AAR procedures for the AE testing of railroad tank cars and a literature review of material relevant to this area of study. Chapter 3 describes the experimental program and test results on a general purpose tank car. Chapter 4 focuses on the experimental program and test results on the pressure car. Chapter 5 follows the same format and discusses the tests conducted on the bar-reinforced tank car. Finally, chapter 6 concludes with a discussion of key findings from this study and suggestions for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 AAR PROCEDURE FOR AE TESTING OF RAILROAD TANK CARS

Principles of acoustic emission, instrumentation and data acquisition methods related to AE inspection are not discussed in this thesis. There is a wealth of literature devoted to the discussion of these topics (McMaster 1987; Williams 1980).

2.1.1 Overview of Existing Procedure

The existing Association of American Railroads (AAR) procedure for the acoustic emission testing of railroad tank cars (AAR 1999) was developed as a method for assessing the structural integrity of railroad tank cars. The procedure applies to new and in-service tank cars constructed of carbon steel, stainless steel, aluminum, and other metals.

The AAR procedure calls for a structural analysis to be performed on a representative tank car design for the specified loadings in the AAR procedure.

This is due to the fact that during an AE test, defects are only detected in areas that are stressed by the applied loads. The analysis required by the AAR procedure may be either based on a finite element analysis or experimental strain measurement. The representative tank car is defined as one that has the same design configuration in terms of sill, tank, and head block to the one that is the focus of the AE test. Slight design variations in the tank car to be tested from the representative one analyzed are permitted provided that corrections to the stress magnitudes are made. The analysis is required to ensure that the areas of the tank car that are of interest are stressed adequately during the test (AAR 1999).

The stressing components of the AE testing procedure consist of two types of loads, the torsion loading (Jacking Test) and the pressure test. The order of these tests is only important for new tank cars and in-service cars pressure tested above the set point of the relief valve or the burst pressure of the safety vent. An additional torsion loading (Twist Bar) applied to the end of the sill is part of an annex to the AAR procedures.

2.1.2 Pressure Loading

The pressurization of the tank car in the AAR procedure is based on the tank's pressure rating and the service history of the tank car six months prior to performing the AE test. Typically, for in-service tanks the maximum AE test pressure is 90% of either the set point of the relief valve or the burst pressure of the safety vent. The pressure test is generally thought to be able to assess the structural integrity of the tank, including the nozzles and sumps as well as all parts of the pressure envelope. Defects such as corrosion, bad welds, pits and cracks that are adequately stressed during the pressurization are typically detected. Some of the unstressed locations identified in the AAR procedure are ladder attachments, side safety rail attachments, and other non-pressure containing parts of the tank shell. Also, AE testing will not detect defects in flexible linings. Additional areas, including major structural components of a tank car have been identified as part of this research as areas not adequately stressed. There are also special pressurization procedures described in the AAR procedure for the early detection of stress corrosion cracking.

2.1.3 Torsion Loading (Bolster Jacking)

The procedure also specifies a torsion load to be applied to the tank car with a jack so that the tank car is twisted. One lift is performed on each end of the car, with both the lifts on the same side. The specified lift is defined in terms of a deflection at the bolster where the load is applied. Different deflections are to be applied if the tank car is empty or full of liquid. 2 in. of deflection are specified for an empty tank car and 1 in. for a full car. According to the procedure, a more thorough evaluation is obtained when the tank car is filled with liquid. The purpose of this test is to detect cracks, corrosion, and other defects in the sill and tank cradle pads as well as in the welds attaching these pads to the tank, sill and bolster. Defects in the head block region of an empty tank car and in the sill outboard of the tank are not detected by this procedure. A special jacking procedure known as the twist bar test (an annex to the standard procedure) may be used as an additional procedure for the detection of some of these defects (AAR 1999).

2.2 ACOUSTIC EMISSION AND STRESS CONDITIONS

Acoustic emission is most commonly detected in metals during deformation caused by an applied stress. There are other processes that produce acoustic emission such as certain corrosion reactions. However, these will not be the focus of the following discussion. Rather, the discussion will focus mainly on the acoustic emission produced from fatigue cracks under an applied stress. Of relevance is the production of acoustic emission from dislocation motion, twinning, and decohesion or fracture of inclusions and precipitates. Heiple and Carpenter provide an extensive review of literature on acoustic emission from these sources (Hieple and Carpenter 1987)

McBride (1994) conducted a series of experiments to investigate the behavior of fatigue cracks under load hold. It was observed that the crack growth AE activity is seen to occur during increases in the load to loads greater than the maximum fatigue load. It was also found that some activity could occur during the load hold time especially for large cracks under plane stress conditions. Further tests conducted by McBride on steel, Zircalloy and 7075 aluminum showed that the load hold test can detect fatigue cracks if:

$$K_{lh} \geq 0.4K_{IC}$$

Where K_{lh} is the mode-I stress intensity factor during load hold and K_{IC} is the plain strain fracture toughness. Furthermore, it was shown that there was a linear relationship between the number of detected acoustic emission events and the amount of crack growth for steels undergoing cyclic loading. The same relation applied to all steels but the rate of detected AE with respect to crack growth rate was found to be dependent on the material, heat treatment and instrumentation. McBride also found that a crack growth increment of at least 0.5 mm^2 was required of a fatigue crack to produce a detectable AE signal during an AE test.

The load history was identified as an important parameter that could affect the results of an acoustic emission test. Tests from the same report stated that acoustic emission due to crack growth could be detected if the test load exceeded the recent maximum load prior to the test. The results also demonstrated the dependence of the estimated severity on the load history. It is important to note that the Kaiser effect will most likely not be observed during the AE testing of railroad tank cars. The Kaiser effect is the absence of detectable acoustic emission at a fixed sensitivity level, until the previously applied stress levels are exceeded (ASTM 1999). If the conditions of the Kaiser effect are examined in detail, they are usually never satisfied. "Defects" are usually altered during unloading, reloading, or between loading and reloading. In most cases it is the Felicity effect that will be observed during the AE testing of railroad tank cars enabling the detection of significant structural defect(s) (Fowler 1992). The Felicity effect is the presence of detectable acoustic emission at a fixed sensitivity level at stress levels below those previously applied (ASTM 1999).

2.3 EVALUATION OF STRESS CRITERIA

There are various sources of acoustic emission in a metal subjected to an applied stress. In determining the success of a stressing procedure, there are only a few criteria that can be used to qualify a loading procedure. The most common of these is the 10 percent of yield stress criterion.

2.3.1 The 10 Percent of Yield Stress Criterion

This criterion states that reaching a gross stress of 10 percent of the yield stress (σ_y) in the component or structure to be tested is enough to generate significant acoustic emission. It is normally assumed that the component is under tensile stress. However, the AAR procedure does not restrict the stress in this manner. The 10 percent of yield stress criterion is based on experimental data from uniaxial tensile tests on metals that indicate that significant acoustic emission starts when the tensile stress reaches $0.9\sigma_y$ (Fowler 1999). This criterion is based on forcing conditions necessary for dislocation to occur at the crack tip. Using a stress concentration factor obtained from assumptions of crack tip depth and radius, the stress required to assure 90% of yield at the tip of a crack (with the lowest expected stress concentration) is approximated at 10 percent.

The crack is modeled as an elliptical U-shaped notch in tension. Various empirical equations or others derived by relating the stress concentration factor to the stress intensity factor can be used to determine the stress concentration at the crack tip (Pilkey 1997). A common expression used to determine the stress concentration factor for an elliptical or U-shaped notch in a semi-infinite thin element in tension is given by:

$$K_{fc} = 1 + 2\sqrt{\frac{t}{r}}$$

K_{fc} is the stress concentration factor of the crack idealized as a U-shaped notch, and *t* and *r* are the depth and radius of this idealized crack. This criterion does not directly take into account mechanisms such as micro cracking, crack advance, deformation twinning as well as inclusion fracture and decohesion. However, an increasing tensile stress will cause emission from these sources to increase.

2.3.2 Compressive Stresses and Other Stress States

Hamstad, Peterson, and Mukherjee (1979) have shown that the stress state significantly alters the acoustic emission from a given material. In tests on various steels, more acoustic emission occurred at lower strains from uniform biaxial loading as compared with the uniaxial stress state.

Acoustic emission created by dislocation motion (the main source of emission) is not dependant on the deformation mode (tension or compression). Hadjicostis and Carpenter (1980) conducted compressive tests on hot and cold rolled steels and found a good correlation between acoustic emission and compressive plastic strains. In addition, the testing mode has a major influence on the acoustic emission produced from twinning and inclusion fracture (Hieple and Carpenter 1987). A tensile stress is certainly more favorable in contributing to inclusion fracture or crack advance than is a compressive stress.

No criterion takes into account the beneficial effects of compressive stresses in stimulating acoustic emission from fatigue cracks. Barnes (n.d.) has shown that in the presence of high compressive stresses, notched specimen in bending generate significant acoustic emission at stresses well below nominal yield on the surface of the specimen.

The experiments reported in chapters 3 through 5 of this thesis reveal high compressive stresses to occur in areas where cracks are usually detected by the existing AAR procedures. An example of these areas is the termination of the bolster cradle pad into the tank car shell; this area experiences a high compressive force when a jacking load is applied under the bolster. As discussed in section 3.3.5 defects in this area have been detected by AE generated by the jacking test. The applied jacking load causes compressive membrane stresses to occur in the bolster region. Local bending also occurs so that tensile stresses may occur on the inside wall (Wichman, Hopper, and Mershon 1969).

2.4 RESPONSE OF RAILROAD TANK CARS TO AAR PROCEDURE LOADS

2.4.1 Loading Aspects

McBride (1994) studied the existing AE procedures for railroad tank cars and suggested ways for improving the existing procedure to the Transportation

Development Center at Transport Canada. The main recommendations and observations of his study are:

i. The current AAR procedure is acceptable for adoption in its current form and provides a procedure that can detect structurally significant defects in railroad tank cars.
ii. Strain gage data should be required to substantiate the jacking and twist bar tests as they are applied to each individual stub sill design.

Pollock (1995) performed the second major work to study the existing AAR procedure and investigate, even though hypothetically, the plausibility of other stressing techniques. In this report, questions were raised about the need for changing the applied stimulus to be specific to different car/sill designs.

In the standard AAR procedure, the jacking under the bolsters or under the sill with a twist bar is defined in terms of a displacement. Pollock questioned the possibility of using the load rather than displacement as a measure of specifying the stressing stimulus. This concern is addressed in a latter part of this study. There were also concerns that there exist certain types of railroad tank cars that are simply unsuitable for AE testing.

It had been widely perceived that the existing bolster jacking stressing technique induces a large amount of twist into a tank car. The tests conducted by

Pollock established the extent of the variability involved and stressed the need for a better understanding of the boundary conditions. During a standard AE test, only one of the boundary conditions is specified (the displacement at the bolster that is being jacked). However, the interaction with the other boundary conditions will influence the stresses induced in the railroad tank car.

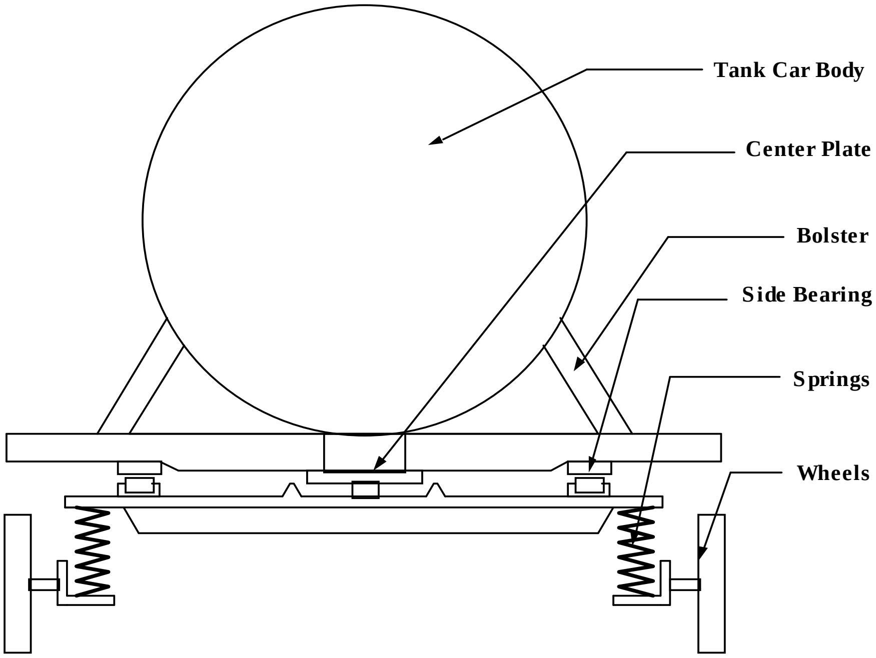

Figure 2.1 End View of Railroad Tank Car Showing Contact Regions

2.4.2 Mechanics of Tank Car Response to Bolster Jacking Loads

There are twelve contact points on a railroad tank car through which an external force can be impressed in service or during an AE test. These contact regions are the two couplers, the four bolster jacking points, the four side bearings and the two center plates. Figure 2.1 shows an end view of a typical railroad tank car with some of these contact regions.

The unattached car is supported on the two center plates at each end of the railroad tank car. Filling the tank car with liquid will result in the compression of the springs and a readjustment of the supporting forces to maintain equilibrium. During the rolling motion of the car body, one or more of the side bearings may close, whereupon the new forces will enter the car through the newly established contact points.

The displacements described in the AE procedure are not completely translated into deformation of the tank car or stressing its body. In trying to better improve the existing procedure, it is important to analyze them and understand what part of the applied displacement is associated with elastic deformation.

Pollock (1995) identified that during the standard jacking or twist bar tests. The mechanical response can be broken down into these components:

i. Elastic deformation of the structural members.
ii. Rolling of the car on the center plate.

iii. Overcoming the frictional resistance of the side bearings. Deformation of the side bearing may also influence the mechanical response.
iv. Changes in the compression of the springs.
v. Plastic deformation and free play.

Based on experimental investigations, roll was the largest component of the displacement applied during the bolster and sill jacking tests. Roll accounted for at least 50% of the movement at the loading point for both the bolster and sill jacking tests.

As for the sill twist tests, much less roll and pitch occurred on the full car than on the empty one. This may be due to the settling of the car on the side bearings and the increase weight. Pollock also observed a greater or comparable elastic deformation in the full car. In general it was found that the elastic deformation contributed to only a small portion of the total deflection at the loading point. It was 13% on average for the bolster jacking tests and 7% on average for the sill twist tests. Analysis of the mechanics involved in a pressure test was found to be simpler in that all the forces generated are internal to the tank car. The side bearings and center plates have a minimal effect on the stresses produced.

CHAPTER 3

BEHAVIOR OF A GENERAL PURPOSE TANK CAR UNDER LOADING STIMULI

3.1 INTRODUCTION

A general purpose tank car was tested in the Phil M. Ferguson Structural Engineering Laboratory at the University of Texas at Austin. The car was a US Department of Transportation (DOT) specification 111A100-W1. This type of tank car is generally involved in the transportation of non-hazardous materials at low pressure such as corn syrup or liquid detergent.

The design of this tank car is of the typical stub-sill design with a shell thickness of 15/32 in. and a head thickness of 0.5 in. ASTM A-515-70 grade steel was used for the main cylindrical portion. Union Tank Car Company built this car in March 1969 (UTLX 48696). This car was non-jacketed and had no heavy bottom attachments. Figure 3.1 shows an overall view of this tank car.

Figure 3.1 Overall view of General Purpose Tank Car

3.2 EXPERIMENTAL PROGRAM

Sections 3.2.1 and 3.2.2 present a discussion of the instrumentation and important issues related to strain gauging. This information is applicable to the other tested tank cars. Minor differences in instrumentation for the tests on the other cars are described in chapters 4 and 5.

3.2.1 Instrumentation

The experimental stress analysis on this tank car was conducted by measuring the strains on the surface using electrical-resistance strain gauges. A measure of stress was obtained by multiplying the strain with the modulus of elasticity of steel (29 x 10^6 psi). This measure ignores Poisson's ratio effect. In all the evaluated loads (excluding pressure tests), the strains transverse to the welds were greater than those in the longitudinal direction. For the pressure test, the hoop stress is twice the longitudinal and the approximation used may introduce more error. However for the pressure test, the maximum stress at the discontinuities such as the bolster and headblock will be less affected because of the directional amplification of stress in the direction where the stress concentration factor applies. Strain gauges were mainly oriented in either the hoop or longitudinal directions. Several strain gauge rosettes were also used to determine the principal stresses at some locations. The areas investigated on this tank car are shown in Figure 3.2.

The symmetrical structure of a railroad tank car made it possible to instrument only one quadrant. The standard industry convention for naming the quadrants of a tank car is done by establishing the end where the brake handle is located as the B-end and then labeling the sides of the car as left (L) and right (R) when looking at the B-end. The other end of the car is the A-end. Figure 3.3 shows this naming convention. The BR quadrant of the tank car was the strain-gauged quadrant.

Sixty strain gauges were attached to the tank car in quadrant BR. However, not all these gauges were active for all the tests as some gauges had to

Figure 3.2 Strain Gauge Locations

be installed when a certain area needed further examination. Most of the strain gauges were placed perpendicular to locations of potential fatigue cracks, namely the welds. Strain gauges were occasionally placed parallel to these locations to achieve a better understanding of the state of stress. The strain gauges were typically placed about 2.5 in. away from a weld or geometric discontinuity.

The uniaxial strain gauges used were manufactured by Measurements Group and had the specification EA-06-250BG-120. These strain gauges had a gauge length of 0.250 in. and a grid width of 0.125 in. Their resistance was 120.0 ± 0.4 % ohms. The transverse sensitivity of these gauges was 0.7 ± 0.2 %. A Hewlett Packard (HP 3852A) data acquisition system was used to measure the strains, loads and displacements. These quantities were measured every 2 seconds.

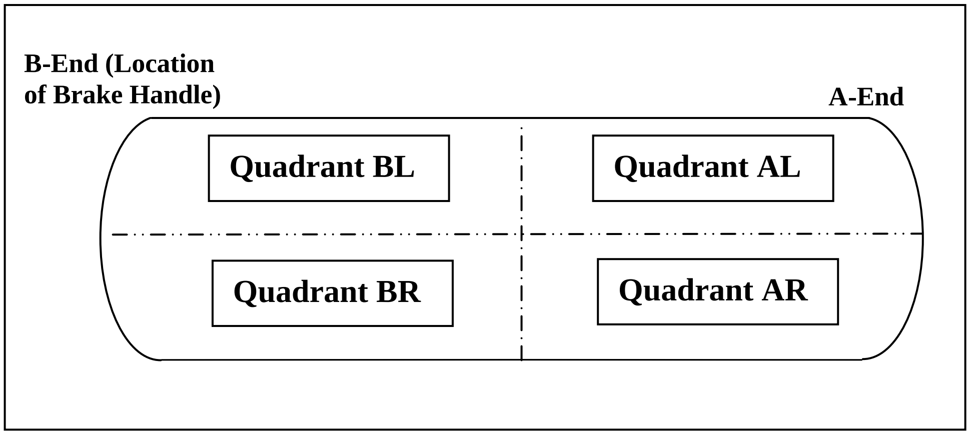

Figure 3.3 Standard Labeling of Tank Car Quadrants

A load cell was used for all the tests that involved jacking under the bolsters or sills. The maximum capacity of the load cell was 100,000 lb. A linear potentiometer (LP) measured the displacement at the jacking location. In some tests, displacements occurring at other locations of the tank car were also measured. The accuracy of the recorded data is as follows: the measured strains are within $\pm 5 \times 10^{-6}$, the load is within ± 25 lb., and the displacement is within 0.5×10^{-3} in.

3.2.2 Strain Gauging and Local Stress Concentrations

An integral part of testing all the railroad tank cars involved the measurement of strains near locations where fatigue cracks are expected to occur. Almost exclusively, these cracks are found to occur in the vicinity of welds joining different parts of the tank car body together or attaching the tank car to other structural components such as the sill.

The 10 percent of yield stress criterion (see Chapter 2) takes into account the stress concentration at an idealized crack tip but does not account for the increase in stress in the vicinity of welds. The stress measured at a strain gauge located 2.5 in. away from a weld will be lower than the local stress at that weld. Thus a fatigue crack in the vicinity of a weld is in a state of multiple stress concentration. A geometric stress concentration may also occur from a change in shape (e.g. cylinder/head junction). The multiple stress concentration factor K_{eff}, in this idealized model for the tip of the fatigue crack is given by:

$$K_{eff} = K_{fc} \cdot K_g \cdot K_w$$

Where K_{fc} is the stress concentration at the tip of the crack and K_g is the geometric stress concentration factor. The stress concentration factor due to the weld K_w, can be adequately approximated as a trapezoidal protuberance (Pilkey 1997). A stress concentration factor K_w of 1.55 is obtained for the geometry of a typical weld bead. Despite this idealization, experimental results indicate that higher stress concentrations occur than predicted by the models above (Pilkey 1997).

Caution was exercised in the placement of strain gauges to avoid areas of local stress concentrations. However, the possibility of a local stress concentration from the applied loading cannot be excluded. Areas with high stress gradients and complex stress fields (e.g. the headblock) require careful analysis. Other experimental techniques such as stress coating, or a finite element analysis (FEA) are required to obtain a better understanding of the state of stress in these areas.

3.2.3 Bolster Jacking Tests

Standard jacking under the bolster tests like those mandated by the AAR procedure were performed on this tank car (AAR 1999). The bolsters were lifted to approximately 2.5 in. for the empty car instead of the standard 2 in. In some of these tests, the movement of all the bolsters was monitored during the jacking process (Figure 3.6). These tests were conducted for all the four bolsters and then repeated with the tank car full of water. The displacement of the lifted bolster was also limited to 2.5 in. when the tank car was full.

3.2.4 Sill Jacking Tests

Jacking under the sill was investigated as a possible method of stressing the tank car. It was initially believed that a load of this kind would produce a behavior resembling that of a cantilever characterized by higher stresses away from the load. The point of load application was the sill striker plate. The lift at the striker plate for the empty car was about 3 in. and a little over 1 in. for the full car. Figure 3.4 shows a schematic of this jacking procedure.

Another test was also conducted on the empty tank car. The displacements at the sill, its inboard termination point at both ends and the center of the tank car were measured. The motivation for this test was to investigate whether the tank car behaves like a cantilever under such a load.

3.2.5 Pressure Test

A pressure test was performed on this general purpose car per the AAR procedure (AAR 1999). The pressure was increased slightly higher than the 90 % set pressure of the relief valve (67.5 psig). The stresses in the tank car were monitored up to 70 psig. A pressure gage was used to read the pressures, and a data acquisition system was used to capture the strains.

3.2.6 Sill Twist Tests

Sill Twist (Twist Bar) tests were performed on the general purpose tank car. Two tests on the empty and full car were conducted on each side of the sill at the B-end.

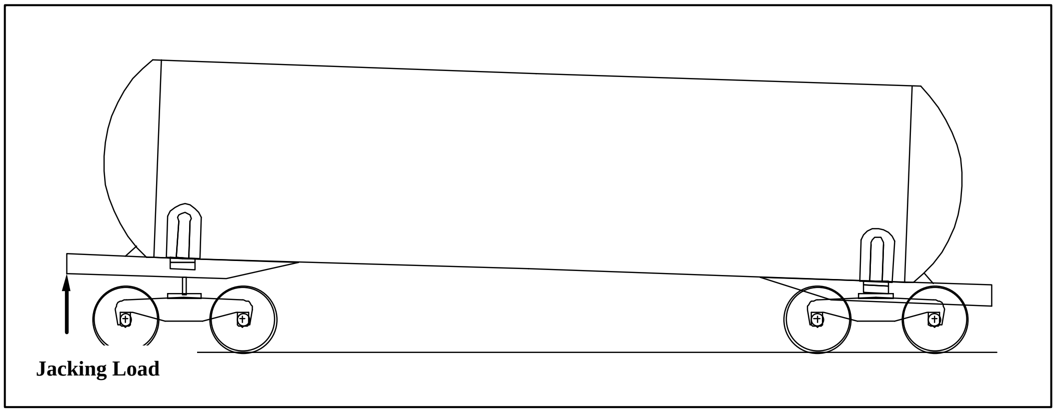

Figure 3.4 Schematic of Jacking Under the Sill Striker Plate of a Tank Car

The load and displacement were measured for this test. The displacement was not measured in the same way as that specified in the procedure (AAR 1999), but rather the point of measurement was the location of load application. Figure 3.5 shows the setup used for this test. To reduce the slack in the twist bar before the load was applied, the gap under the twist-bar away from the grip location was shimmed with appropriately sized steel plates. The actual procedure eliminates the problem of accounting for slack by measuring the displacement at the rail using a pointer extending from the sill. This ensures measurement of the sill's displacement and not that of the twist bar.

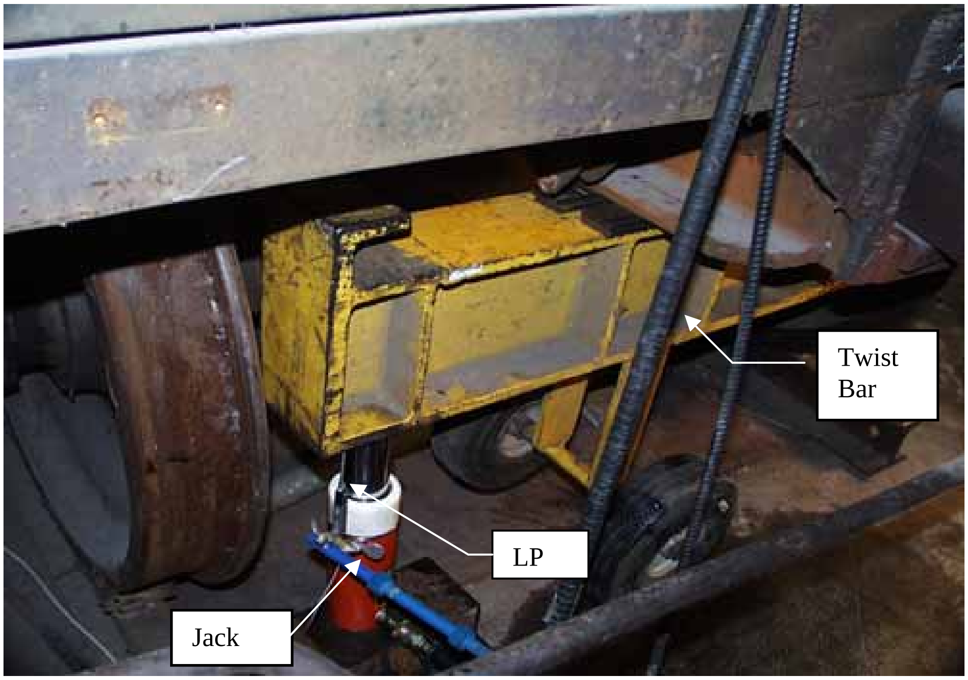

Figure 3.5 Typical Test Setup for a Twist Bar Test on a Railroad Tank Car

3.3 TEST RESULTS FOR THE GENERAL PURPOSE TANK CAR

3.3.1 Load-Displacement Behavior from the Bolster Jacking Tests

The first test involved monitoring the displacements of all the bolsters when lifting under one bolster. Figure 3.6 shows the large movements occurring at all the bolsters due to this type of loading. Research reported by Pollock (1995) finds that most of the applied displacement can be attributed to roll, lift and pitch. According to Pollock, roll contributed to the largest amount of the applied displacement.

The displacement in Figure 3.6 for jacking under the AR bolster confirms that a large portion of displacement is due to roll. The BL and AL show essentially the same displacements. The AR and BR displacements are similar to each other but significantly larger than the L side deflections. It is clear that the car is rolling about the centerline. The reason for the higher displacements of the R side is the lifting of the side caused by the jacking.

Figure 3.7 shows a plot of the load versus displacement under the bolsters from four separate tests on the empty car. The displacements were increased above the 2 in. currently specified by the AAR procedure for the testing of empty cars. The plot shows that increasing the deflection beyond 2 in. will not result in significant additional load being applied to the car. The difference in the load displacement behavior can be attributed to the rolling of the car and the effects of engaging new contact points (Pollock 1995). The difference in the stiffness of the springs influences the shape of the load-displacement curve. Although the behavior is non-linear, the maximum load attained (steady plateau region in Figure 3.6) when jacking from the four tests is within an acceptable range.

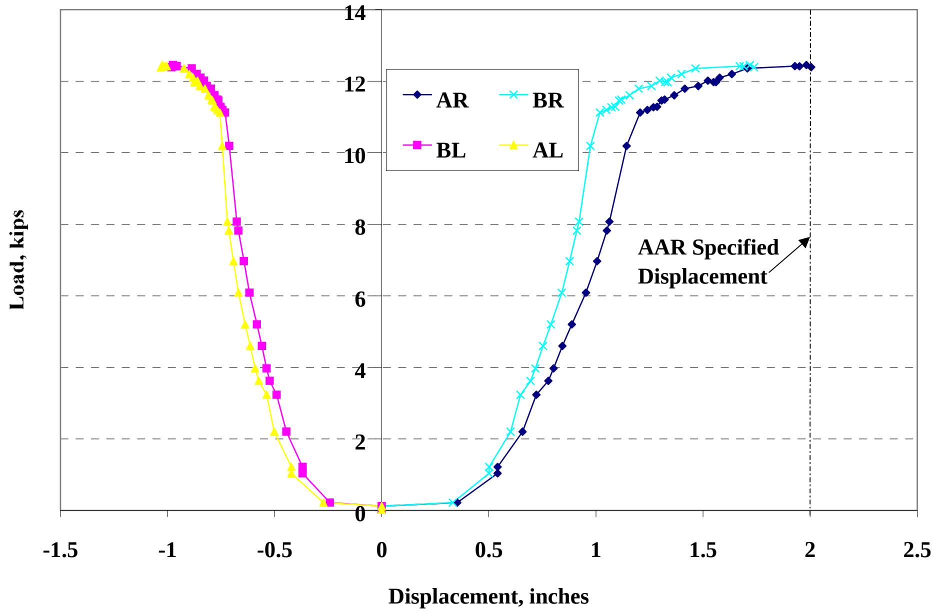

Figure 3.6 Bolster Displacements when Jacking under Bolster AR of the Empty General Purpose Tank Car

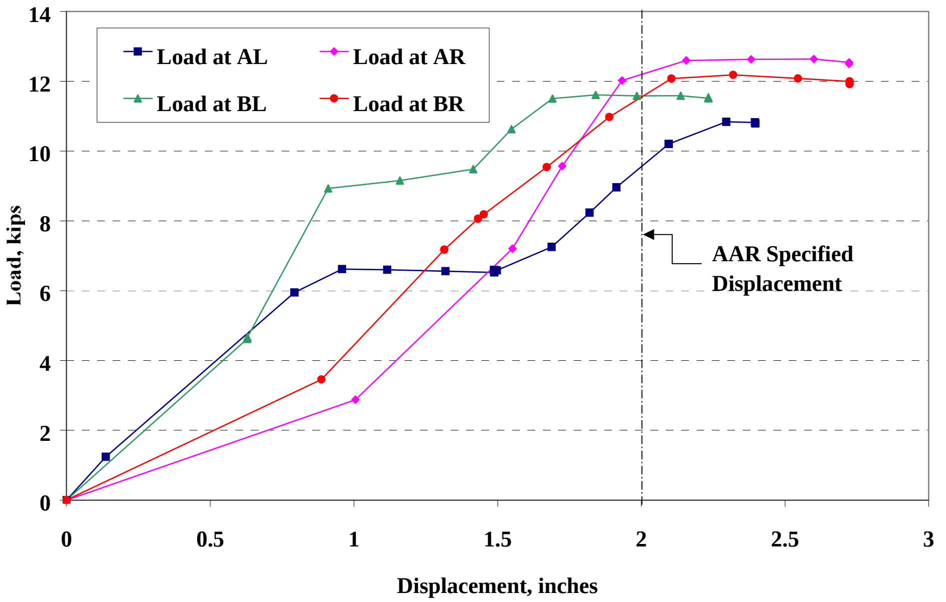

Figure 3.7 Load versus Displacement Behavior for Jacking under the Bolsters of the Empty General Purpose Tank Car

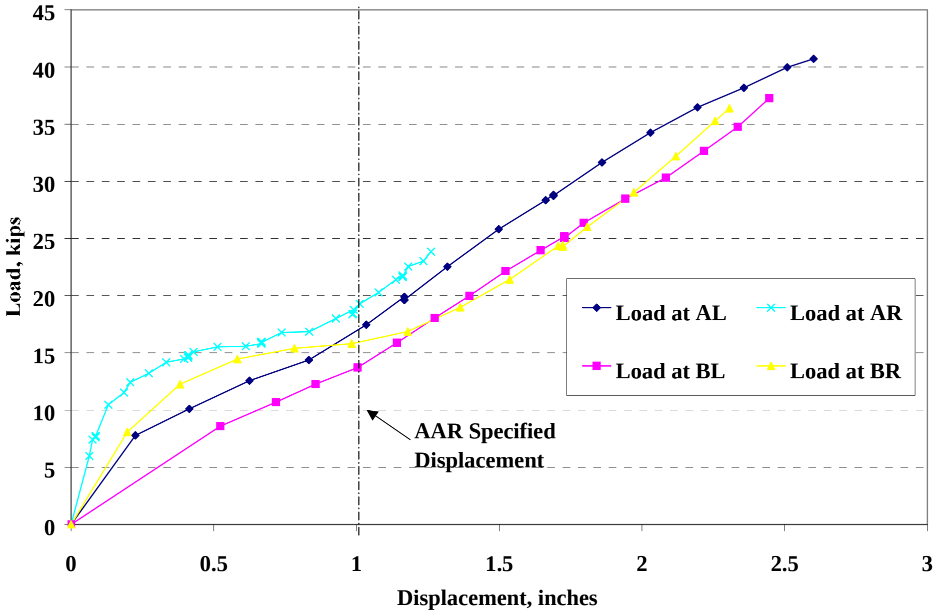

Figure 3.8 Load versus Displacement Behavior for Jacking under the Bolsters of the Full General Purpose Tank Car

When a full tank car is lifted under the bolsters, the behavior is different from that discussed above. The load continues to rise beyond the 1 in. specified for the full car. Figure 3.8 shows this behavior in the load versus displacement curves when jacking separately under the four bolsters of the car. Stresses attributed to jacking under the bolsters are directly related to the magnitude of the load applied. Discussions in upcoming sections will illustrate the importance of considering the stresses caused by the contents of the car. In certain important inspection locations, the stresses caused by the contents can interfere with beneficial stresses caused by the jacking loads.

3.3.2 Load-Displacement Behavior from the Sill Jacking Tests

Figure 3.9 shows a load versus displacement plot for the empty tank car as it is jacked under the striker plate of end B. Note that the maximum load occurs after 1 in. of displacement in this case. Figure 3.9 and analysis of the stresses produced reveal that increasing the displacement beyond 1 in. does not increase the stresses in the car. Figure 3.10 shows the load versus displacement behavior for the same test on a full car. In Figure 3.11, the response of the empty and full car to this type of loading is illustrated. The maximum load that can be applied during any jacking procedure is ultimately controlled by the weight of the car.

3.3.3 Load-Displacement Behavior from the Sill Twist Tests

In contrast to the load displacement curves obtained from jacking under the bolsters of the empty car, the applied load for a twist-bar test on an empty car continues to increase with increasing displacement beyond the values currently specified by the AAR procedure (AAR 1999). Figures 3.12 and 3.13 show the load-displacement curves for the twist bar tests on the empty and full cars. In Figure 3.12 the curves were plotted after accounting for the slack in the twist bar. Figure 3.13 illustrates the effect of not taking the slack into account. A small displacement occurred before any load was applied to the sill. This is why the AAR specifies the use of a pointer attached to the sill measure the displacement.

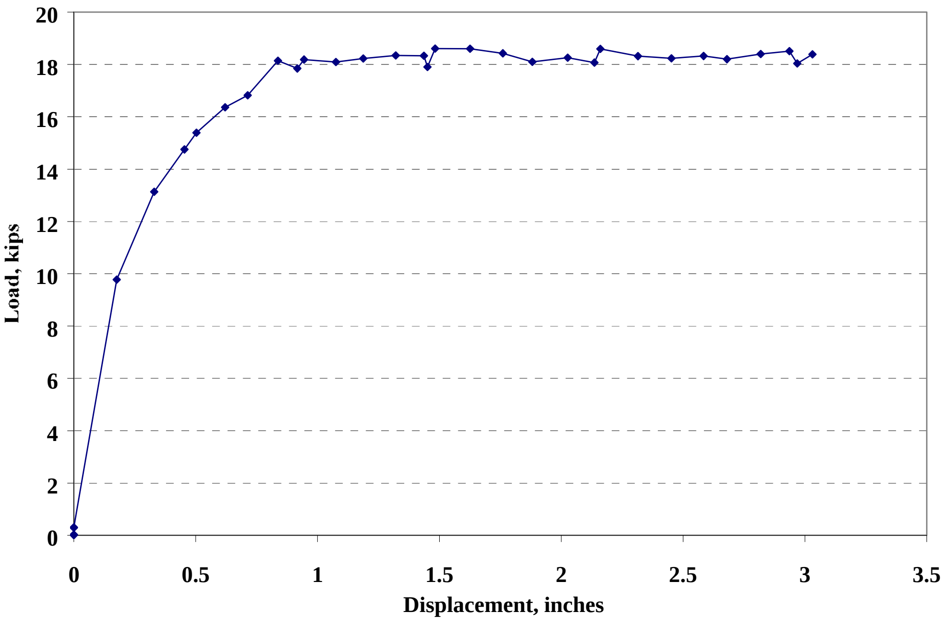

Figure 3.9 Load versus Displacement Behavior for Jacking under the Sill Striker Plate for the Empty General Purpose Tank Car

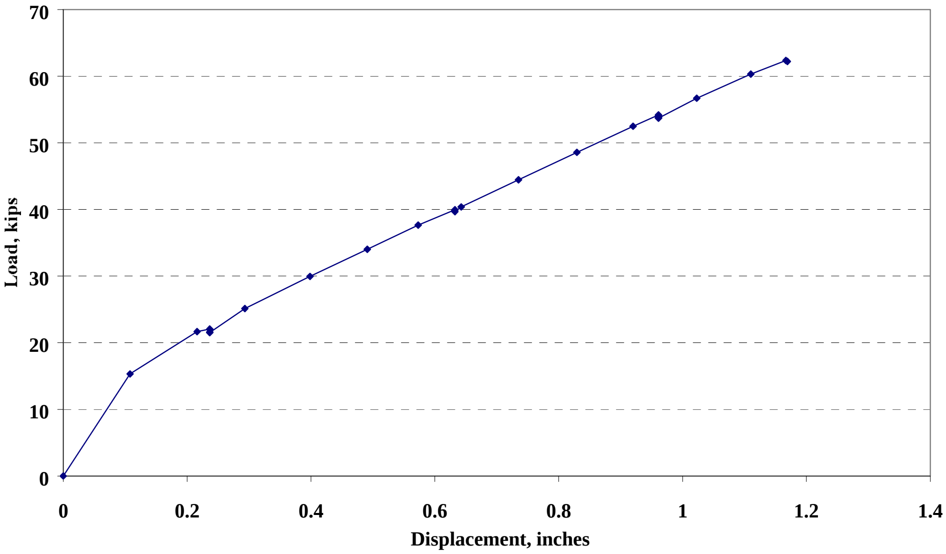

Figure 3.10 Load versus Displacement Behavior for Jacking under the Sill Striker Plate for the Full General Purpose Tank Car

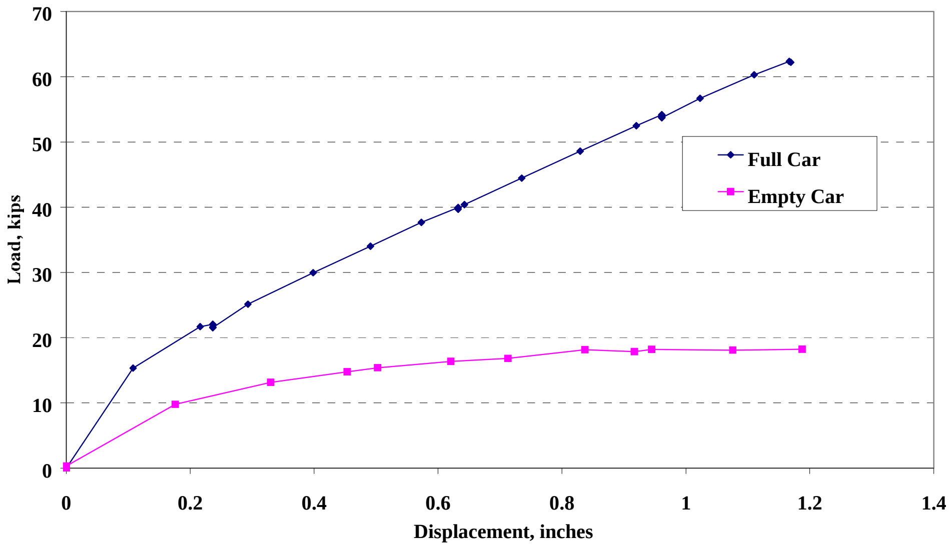

Figure 3.11 Comparison of Load versus Displacement Behavior for a Jacking under the Sill Striker Plate for an Empty and Full Car (End B)

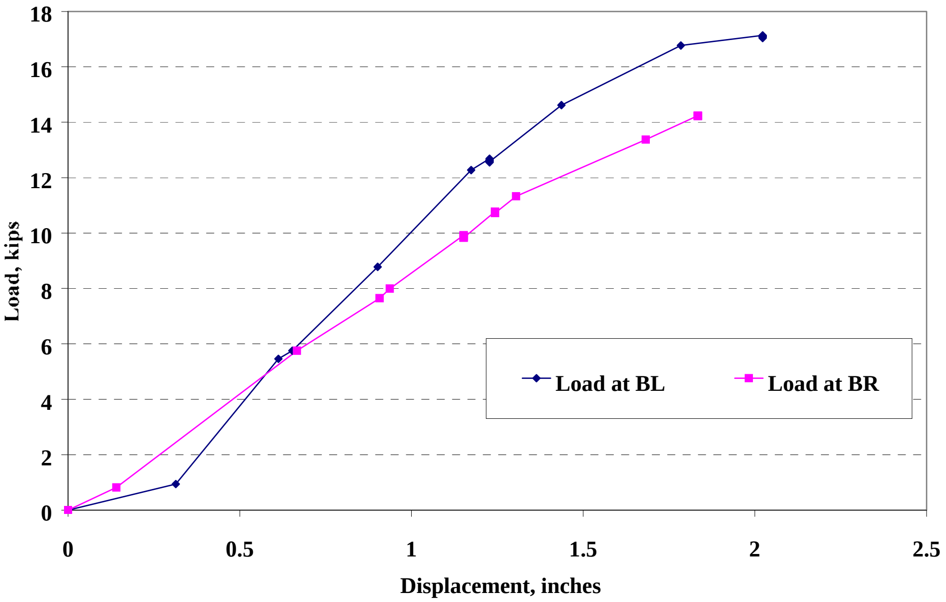

Figure 3.12 Load versus Displacement Behavior for Twist Bar Tests on End B of the Empty General Purpose Tank Car

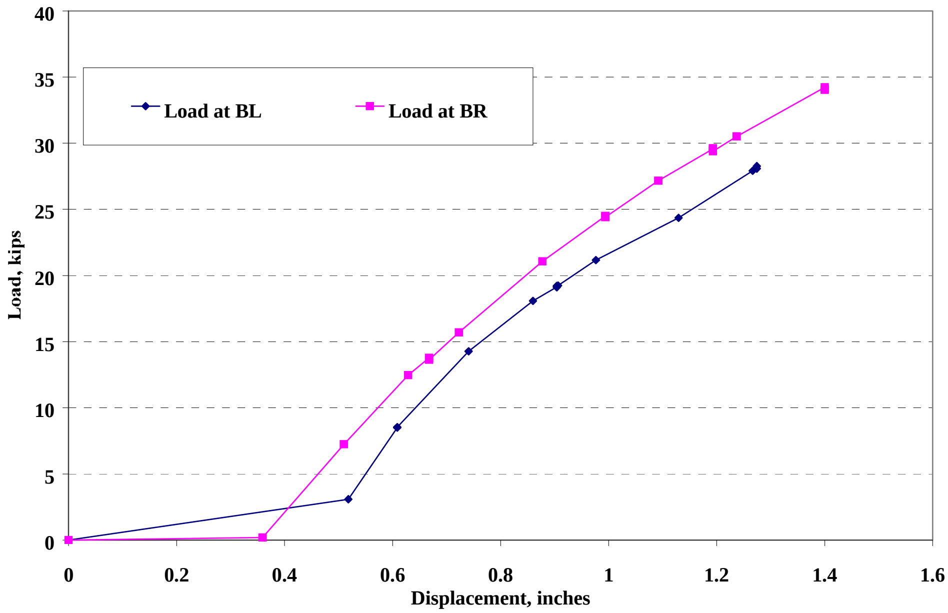

Figure 3.13 Load versus Displacement Behavior for Twist Bar Tests on End B of the Full General Purpose Tank Car

3.3.4 Effect of Tank Car Contents on Stress Conditions

Investigating the effects of the tank car contents on stressing of the car was an important objective of this testing program. Since the contents are a key variable, it was important to understand their effect during AE testing. Stresses due to the contents in a full car are significant in many areas. In some cases they are higher in magnitude than those caused by the applied loads. Table 3.1 summarizes these stresses. Positive stress values in all tables included in this thesis indicate tensile stresses whereas negative values indicate compressive stresses. The following areas were found to experience compressive stresses resulting from the weight of the contents:

i. The sill web inboard of the bolsters.
ii. The area around the inboard termination of the sill into the tank re-pad.
iii. The area on the tank car around the bolster. These compressive stresses become tensile as we move to the top of the bolster.
iv. The welds that run longitudinal to the tank car are controlled by this compressive hoop stress (TS-2 on Figure 3.2). This applies mainly to locations near the sill and bolsters.

Some areas did not experience significant stresses of any magnitude, and other locations experienced tensile stresses higher in magnitude than those caused by the external loading. The main areas that fall in the latter category are the:

i. Girth welds controlled by a high tensile longitudinal stress.
ii. Area around the bottom outlet.

Table 3.1 Key Areas Stressed from Tank Car Contents

Area (See Figure 3.2)	Bolster/sill re-pad intersection (BS-1)	Longitudinal re-pad weld (TS-2)	Center girth weld (GW-C)	Inboard sill web (SL-1)[a]	Inboard sill termination into re-pad (SL-2)
Stress (ksi)	-0.6	-2.1	2.4	-1.8	-1.3

[a] SL-1 is on the sill web at the inboard location of the sill termination into the re-pad.

3.3.5 Stress Conditions from the Bolster Jacking Tests

Tables 3.2 and 3.3 show the average levels of stress generated in the tank car and its attachments from all the tests conducted. In general, the stresses produced from the bolster jacking tests are lower on an empty car than those on a car full of water. However, the effects of the tank car contents can neutralize the beneficial effects of jacking under the bolster of a full car in many locations. The main observations regarding stressing issues in a general purpose tank car from bolster jacking loads are:

i. The stresses generated from elastic deformation on the full car were larger than those on the empty car. However, in many cases the stresses induced are not sufficient to overcome the stresses caused by the contents.

ii. The longitudinal welds that attach the sill-reinforcing pad to the tank shell experienced tensile stresses from jacking under the bolsters of the empty car. This beneficial effect is maximized in the quadrant where the bolster is jacked and is more effective in an empty car due to the effects of the contents overshadowing this effect in the full car.

iii. When jacking under the bolster of an empty tank car, the area around the jacking bolster tends to experience high compressive stresses that get higher as we approach the horns.

iv. The headblock isn’t stressed from bolster jacking on the full or empty car.

Table 3.2 Empty Car

Table 3.3 Full car

Table 3.4 Average Stresses in Key Areas Affected by Jacking under Bolster BR

Load Condition	**Stresses in Key Areas (ksi)** [a]					
	Lower left of bolster	Upper left of bolster	Top of bolster	Lower right of bolster	Upper right of bolster	Long. re-pad welds
2” displacement on empty car	0.4	-1.2	-0.6	0.3	-1.2	0.8
1” displacement + dead weight of water	0.6	-0.8	-1.2	-0.3	-1.8	0.1
Dead weight of water	-0.5	0.7	-0.3	-0.9	0.6	-2.1

[a] Bolster stresses are in the vicinity of bolster BR and are on the tank car shell.

A closer examination of stresses reveals that compressive stresses also occur at the bolster on the opposite side and end of the car (diagonally opposite). For example, when jacking under bolster BR, bolster AL experienced a similar effect but reduced significantly in magnitude. On a full tank car, the area of high compressive stresses also occurs under the jacking bolster, but the effect on the other bolster is less pronounced compared to that of the empty car. Table 3.4 shows the stresses in major areas stressed during empty and full car tests.

Figures 3.14 and 3.15 show how the stresses around the jacking bolster BR vary with increasing displacement for the empty and full car (recall that quadrant BR was the instrumented quadrant on this car). The stresses in Figure 3.15 from the full tank car test are only the net stresses produced by the jacking and do not include the stresses from the car’s contents. A state of dominant compressive stresses occurs around the end of the jacking bolster for both the full and empty car. Compressive stresses are present in both the hoop and longitudinal directions. Chapter 2 presented research results on acoustic emission from fatigue cracks in a state of compressive stress (Barnes n.d.). From a practical procedural approach, it may be that a high state of compression around a fatigue crack is favorable during acoustic emission testing.

Anecdotal evidence from AE inspectors indicates that the jacking test is able to detect defects on both the jacked side of the bolster and on the opposite side. No cases have been reported of the jacking test not detecting defects at the horn of the bolster (Fowler 2000).

Test results reported by Mostert (1995) appear to be in agreement with the discussion above. An AE test was performed on a general purpose car similar to the one discussed in this chapter. Acoustic emission was found to occur at the end on which the jacking was performed. Since the sensors on the bolsters at each end were teed, it was difficult to determine the quadrant where the emission occurred. However, examining other nearby sensors suggests that the acoustic emission occurred in the quadrant where the jacking was performed. A follow-up dye-penetrant inspection revealed cracking to occur on most of the bolsters of this car. Figure 3.16 shows some of the cracking detected on one of the bolsters (Mostert 1995).

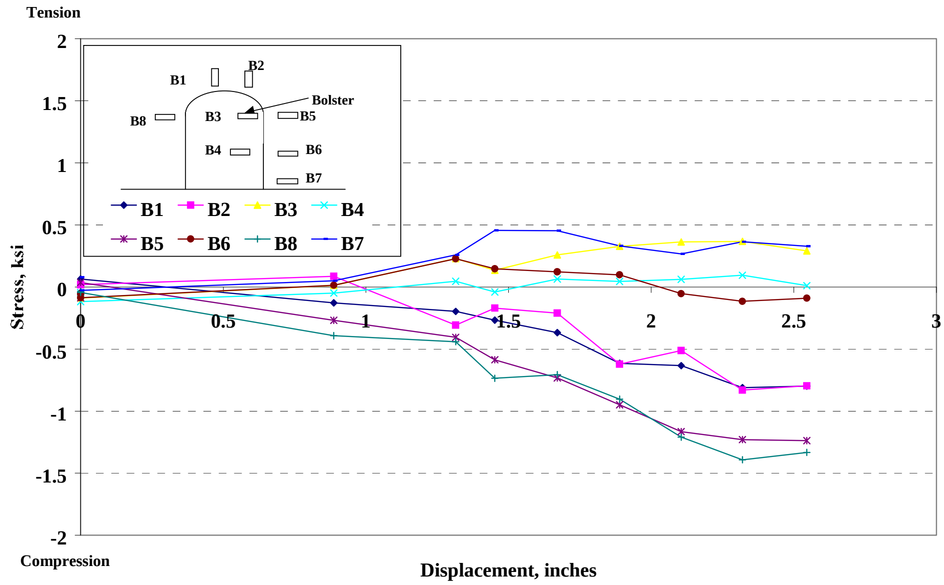

Figure 3.14 Stresses near Bolster BR when Jacking under Bolster BR of the Empty General Purpose Tank Car

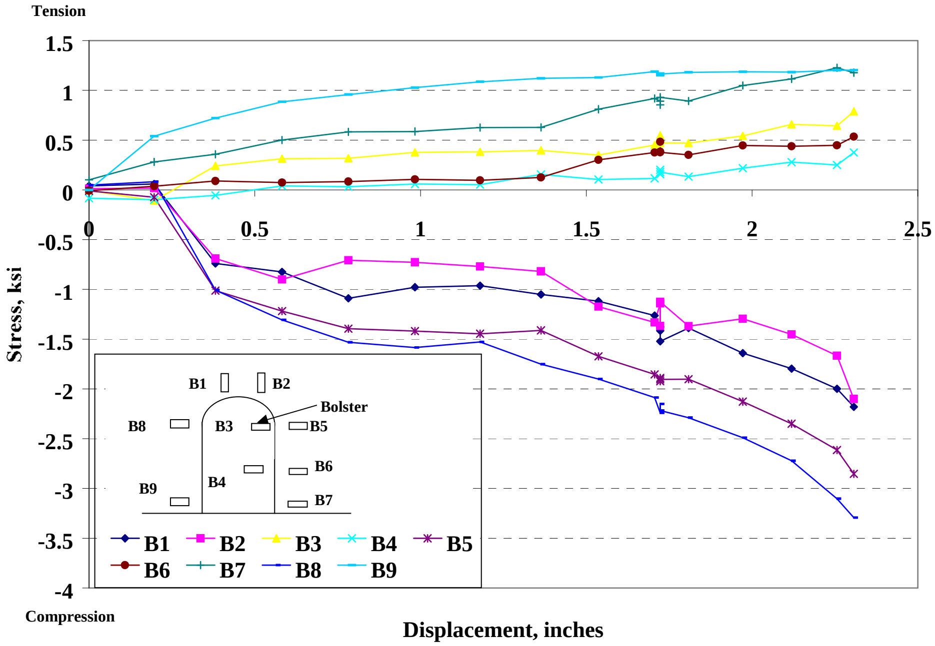

Figure 3.15 Net Stresses near Bolster BR when Jacking under Bolster BR of the Full General Purpose Tank Car

Figure 3.16 Fatigue Cracks Detected During an AE Test (Mostert 1995)

3.3.6 Stress Conditions from the Sill Jacking Tests

Applying a displacement at the sill striker plate of a tank car was found to create favorable stresses in the sill and the inboard termination of the sill into the tank re-pad (see Figures 3.17 and 3.18). Listed below are some of the other stress conditions that result from this type of loading:

i. The headblock region of the tank car at the end where the load is being applied experiences compressive stresses.

ii. The transverse welds attaching the sill re-pad to the tank shell experience significant tensile stresses.

iii. The stresses in the sill are below yield. Damage does not occur in the sill from this loading.

iv. The stressing of the sill, re-pad, and the tank shell is confined to the end under which the loading is applied.

v. Stress levels near the center outlet of the tank car do not reach required levels. The increased span caused by jacking under the sill and removing the support from the center plate to the jacking end does not significantly increasing the stresses at the center of the car.

Additional information about the behavior of a tank car to this type of load is obtained from the second test discussed earlier. In this test several displacements along the car were monitored as the load was applied. The deflected shape of the tank car provided useful information on the actual response. Figure 3.19 shows the profile of these displacements for every 0.5-in. of lift under the sill striker plate. From Figure 3.19, the relative displacement between the sill and the rest of the car indicate the bending of the sill away from the car.

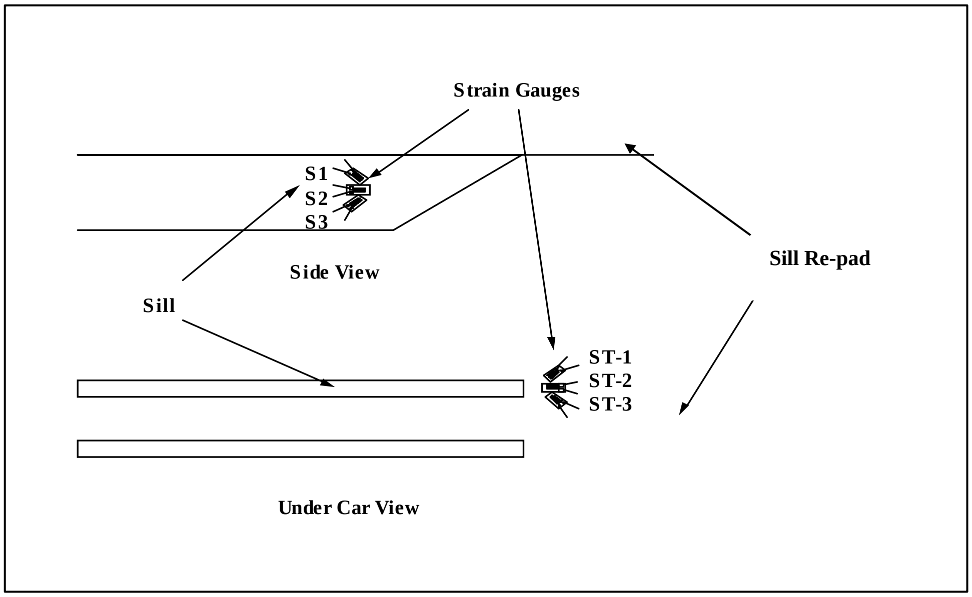

Figure 3.17 Sketch of Strain Gauge Locations on the Sill and its Termination into the Tank Re-pad

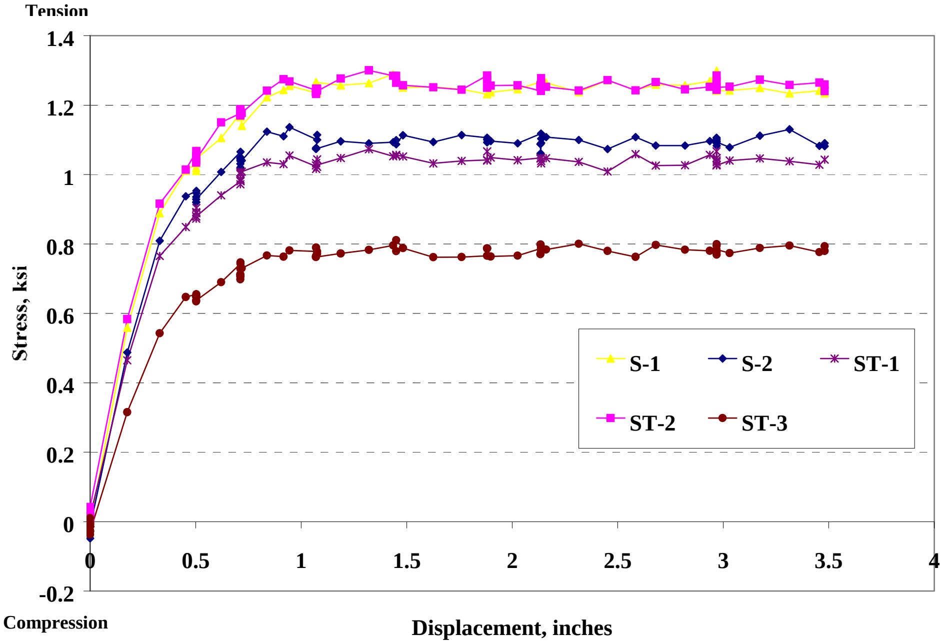

Figure 3.18 Plot of Stresses on the Sill and its Termination into the Sill Re-pad for Jacking Under the Sill at End-B of the Empty General Purpose Tank Car

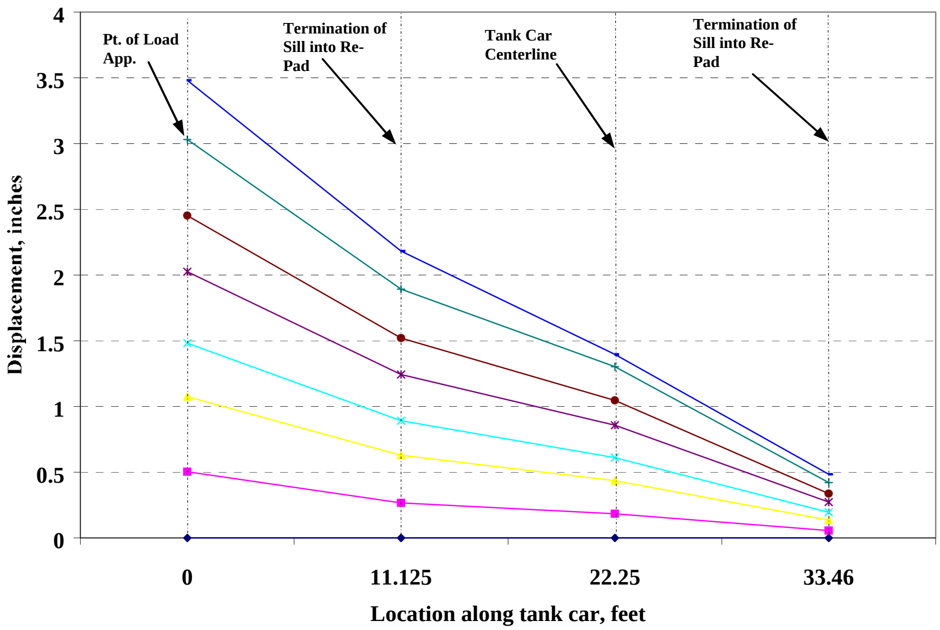

Figure 3.19 Tank Car Profile at 0.5 in. Intervals when Lifting Under the Sill at End B of the Empty General Purpose Tank Car

3.3.7 Stress Conditions from the Sill Twist Tests

AE inspectors report significant success using the twist bar test in detecting defects in the headblock regions of railroad tank cars (Pollock 1995). One of the primary objectives from performing these tests was to ascertain the effectiveness of this technique in stressing the headblock and other areas of the tank car (e.g. longitudinal welds attaching the re-pad to the tank).

Results from the twist-bar tests indicate minimal stressing inboard of the headblock area. Applying a load in a twist-bar test involves applying twist and lift components to the sill (Pollock 1995). These components result in some beneficial stressing in certain areas. Inboard of the bolster, most of the stressing is due to the lift component. This lift component is smaller in magnitude compared to the lift applied during the sill jacking procedure.

Table 3.5 Stresses in the Headblock Region from Twist Bar Tests

Load Condition	**Stresses in Headblock Region (ksi)**			
	Tank shell above headblock (BL side)	Tank Shell in corner above headblock (BR side)	Headblock plate (BR side)	Top plate of sill (outboard, BR side)
Twist BL (empty 1.2", 12.3 kips)	-3.0	-1.4	-0.5	0.1
Twist BR (empty 1.2", 9.9 kips)	-0.4	-0.8	0.8	-3.4
Twist BL (full 1.3", 27.9 kips) + weight of water	-7.1	-1.3	-0.5	0.8
Twist BR (full 1.2", 29.6 kips) + weight of water	-1.6	-1.1	3.0	-9.9
Dead weight of water	-0.3	1.0	0.5	0.2

The geometry of several components coming together in one location coupled with a complex load creates a complex stress field in the headblock region. The lift and twist components of the applied load cause a combined loading condition. This effect from the combined loads can cancel, decrease or increase the local stress. Table 3.5 shows some of the resultant stresses occurring during twist bar tests on this car. The high magnitude of stresses in this area is an important factor in the success of the twist-bar test in this area. A full understanding of the stress field is not possible in this area. Strains collected from a few locations provide useful information of the stress patterns but do not give the complete picture.

3.3.8 Stress Conditions from the Pressure Test

Stresses from the pressure test in the bolster region are shown in Figure 3.20. The load results in high tensile stresses occurring in the area around the instrumented bolster. The locations where the curves intercept the vertical axis are the stresses due to the contents of the full car. Analysis of the stresses produced reveals the effectiveness of the pressure test in generating high tensile stresses in the car’s shell. However, there are several problem areas that are not stressed by this test.

Numerical values of the stresses produced are shown in Tables 3.2 and 3.3. The stresses produced from the pressure test and their effect on generating acoustic emission from a defect are summarized in the following ways:

i. The bolster pad (cradle pad) experiences compressive stresses. This is in contrast to the high tensile stresses produced around the bolster in the tank shell.

ii. The web of the sill remains in a compressive state due to the contents of the car. The tensile recovery in this area from the pressure test is not significant to overcome the preexisting conditions.

iii. The area around the sill termination into the tank car re-pad (SL-2) does not experience significant stresses of any kind from the pressure test.

iv. Tank girth welds and tank welds that run longitudinally with the tank car are stressed well with the pressure test.

v. The area around the bottom center outlet experiences significant tensile stresses although it is heavily reinforced.

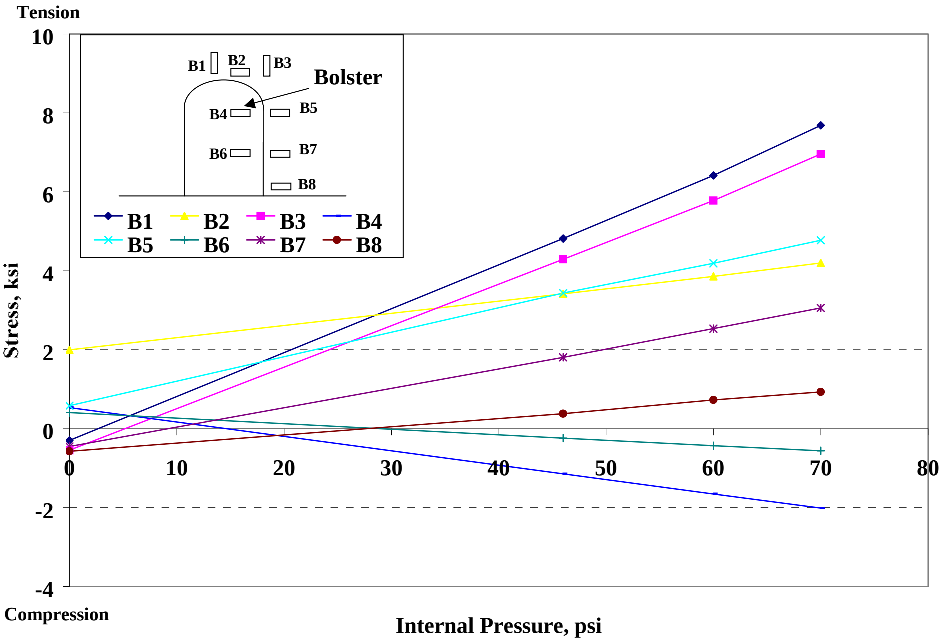

Figure 3.20 Stresses near the Bolster Region of the General Purpose Tank Car during the Pressure Test

CHAPTER 4

BEHAVIOR OF A BAR-REINFORCED GENERAL PURPOSE TANK CAR UNDER LOADING STIMULI

4.1 INTRODUCTION

Railroad tank cars are broadly classified into specific classes or types that have to meet minimum DOT design requirements. About three quarters of the tank car fleet in North America is of type 111. Most general purpose tank cars belong to this class (TRB 1994). The most common design in this class closely resembles the general purpose car tested and discussed in the previous chapter. Some of the general purpose tank cars belonging to type 111 have heavy continuous reinforcement on the bottom shell. It is stated in the AAR procedure that this reinforcement affects the stresses in the car and that the bottom of the car is insufficiently stressed during the application of AAR procedure loads.

The second car tested was of type 111 with heavy continuous reinforcement on the bottom shell (GATX 99982). It had a US DOT specification 111A100W1 and was built in July 1966 by General American Transportation. The safety valve pressure on this car was 75 psi. Most cars of type 111 have a tank wall thickness of approximately 7/16 in. (TRB 1994). The tests on this car were conducted at the GATX facilities in Hearne, Texas. Figure 4.1 shows an overall view of this tank car.

The reinforcement on the bottom shell of the car is shown in Figure 4.2. Usually it is not present in the pressure and most general purpose tank cars. The headblock of this car is shown in Figure 4.3. Standard and modified jacking procedures were conducted on the full and empty car. Experimentation with alternative stressing techniques on this car included the application of vertical loads at the sills and a tensile load on the car through its couplers. A pressure test was also performed. The twist bar test was found to have little influence inboard of the bolsters. The twist bar test was not performed on this car.

Figure 4.1 Overall View of Bar-Reinforced Tank Car

Figure 4.2 Bar-Reinforcement on Tested Railroad Tank Car

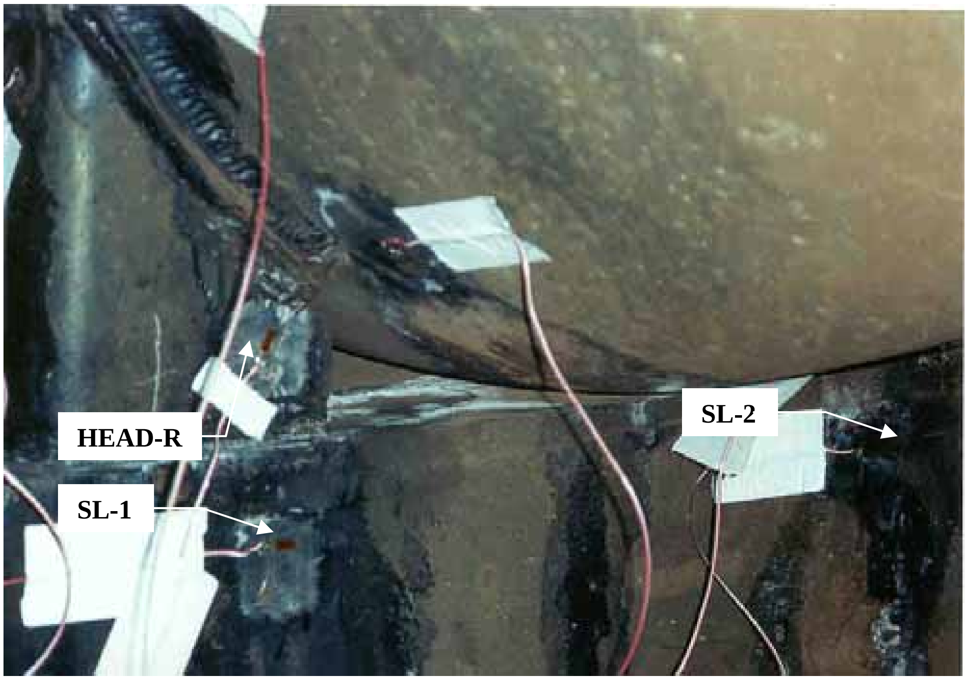

Figure 4.3 Strain Gauges on the Headblock Region of the Bar-Reinforced Tank Car

4.2 EXPERIMENTAL PROGRAM

4.2.1 Instrumentation

Stresses on this car were obtained by measuring the strains on the AL quadrant. Areas of primary focus (i.e. the headblock region and the reinforcing bars on the bottom shell) had more strain gauges installed. Figure 4.4 shows the areas on the bottom shell of this car where strains were measured. Refer to sections to section 3.2 for a complete discussion of the instrumentation used and strain gauging methodology. Strain gauges attached to the headblock are shown in Figure 4.14. In addition, strain gauges were also attached on the reinforcing bars. Linear potentiometers and load cells were used to measure displacements and loads.

4.2.2 Bolster Jacking Tests

AAR (1999) specified bolster jacking loads were applied on this car. The car was tested both full and empty for the first series of tests. In the second series of tests, the effect of roll on the stress field was targeted for reduction by restraining the bolsters on the other side of the car. The restraining of the bolsters was accomplished by the use of hydraulic jacks locked in position to the level of

Figure 4.4 Strain gauges on the bottom shell the bolsters. The modified bolster jacking tests were also conducted on the empty and full car.

Further experimentation with the bolster jacking procedure involved lifting two bolsters at the same time (diagonally opposite bolsters). On the full car, bolster AL was first lifted to 1 in. followed by the lifting of bolster BR to the same displacement. The supports of the car were essentially changed from the center plates to the two bolsters.

4.2.3 Sill Jacking Tests

Jacking under the sill striker plate of this car was performed in a similar manner to that described for the general purpose car in the previous chapter (Section 3.2.4). The testing was conducted at both ends of the full and empty car.

4.2.4 Pressure Test

A pressure test was conducted on this car as described by the AAR procedure (AAR 1999). The strains were measured on the car at 20-psi pressure increments. The maximum test pressure was 67.5 psig, which corresponds to 90% of the safety valve pressure. The internal pressure in the car was measured with a pressure gauge at the top of the car.

4.2.5 Draft Load Test

A draft or tensile load was applied to the bar-reinforced car with the help of a switch engine. Figure 4.5 shows a schematic of the test setup. The switch engine used for this test is shown in Figure 4.6 together with the instrumented car. The data acquisition equipment is on the table in front of the car. In this test, four empty cars with their brakes applied were used to react to the pull of the switch engine. The test car was placed between the switch engine and these four cars.

The switch engine was used to pull the cars gradually. The force applied by the switch engine had to be increased to make the cars move and overcome the static friction. During this period from no load to the onset of movement, the strains were measured continuously in increments of 2 seconds. The applied load was approximately determined by measuring the strains at the front and end couplers of the car. Note that the instrumented car had its brakes on in this test. This resulted in the measurement of different forces at the couplers.

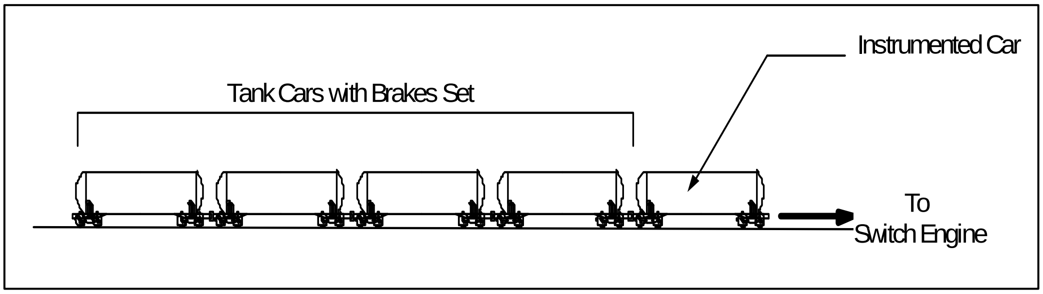

Figure 4.5 Schematic of Draft Load Test on Bar Reinforced Tank Car

Figure 4.6 Switch Engine used to apply Draft Load to Bar Reinforced Tank Car

4.3 TEST RESULTS FOR THE BAR REINFORCED TANK CAR

4.3.1 Load-Displacement Behavior from Bolster Jacking Tests

Figure 4.7 shows the Load-displacement behavior from jacking under the bolsters of the empty car. Displacement data for jacking under bolster AR is not available but the maximum load reached under that bolster was 12.6 kips. It is apparent from the results of the tests on the empty car that the 2 in. deflection specified by the AAR procedure is adequate to reach the maximum possible load. The results on the full car are more variable (Figure 4.8). The load continues to increase beyond the 1 in. specified by the AAR (1999) procedure under some bolsters. Comparison of the load-displacement behavior of the bolster jacking tests on this full car and that conducted on the general purpose car illustrates variability in their behavior. At 1 in. of deflection the load is between 14-20 kips on the general purpose car and between 25-30 kips on the full car. There is less variability between the two cars from the empty tests.

4.3.2 Load-Displacement Behavior from Restrained Bolster Tests

Figures 4.9 and 4.10 show a comparison of the standard bolster jacking behavior with that which occurs when the bolsters on the opposite side are restrained. Consistent with the results obtained from tests on the pressure car (Chapter 5), restraining the bolsters on the other side of the jacking bolster increases the maximum jacking load that can be applied. This may be due to the movement of the support from the side bearing to the other bolster.

4.3.3 Load-Displacement Behavior from Sill Jacking Tests

The maximum load attained at end B of the empty car from jacking under the sill striker was 28.5 kips. A load of 22.0 kips was measured when the jacking was performed at end A. On the other hand, for the full car, the maximum load attained at the jack was 47.9 kips at end A and 47.5 kips at end B. Stress conditions are shown in Tables 4.2 and 4.3.

4.3.4 Effect of Tank Car Contents on Stress Conditions

Summarized in Tables 4.1 and 4.2 are the stresses on this car from all the tests conducted. The contents of the car result in high stresses occurring in many areas. The main areas that experience high stresses from the contents are:

i. The area around the inboard termination of the sill re-pad into the tank shell (SH-2).
ii. The area around termination of the middle reinforcing bar into the tank shell (BAR-T1).
iii. Girth welds.

4.3.5 Stress Conditions from Bolster Jacking Tests

Figure 4.11 shows the stresses near the jacking bolster AL for the empty car. The jump in the stresses may be attributed to the creation of a new contact point on the opposite side bearing during the load application. The stresses in the full car are more uniform as seen in Figure 4.12. Table 4.1 illustrates the low stresses that occur in the headblock region.

Table 4.1 Stresses in the Headblock Region from Bolster Jacking Tests

Load Condition	Stresses in the Headblock Region at End A[a, c], (ksi)					
	HB1	HB2	HB3	HB4	HB5	HB6
Load at AR (Empty-2 in.)	0.0	-0.1	0.1	-0.1	-0.2	-0.2
Load at AL (Empty-2 in.)	-0.1	0.0	0.0	-0.1	-0.1	0.1
Load at AR (Full[b]-1 in.)	0.1	0.0	0.1	0.2	-0.1	-0.8
Load at AL (Full[b]-1 in.)	-0.2	-0.1	-0.2	-0.1	-0.4	-0.3
Contents	-0.8	0.2	-0.2	0.2	0.0	-0.4

[a] Refer to Figure 4.14 for strain gauge locations
[b] Stresses are inclusive of those caused by the car’s contents
[c] Refer to Figure 4.14 for stress near the headblock from the pressure test

4.3.6 Stress Conditions from Restrained Bolster Tests

Altering the standard bolster jacking procedures does not significantly change the stressing condition of the car. The restraining process increases the load and thus the localized compression around the jacking bolster (Tables 4.2 and 4.3). In addition, this test and supporting the full car on bolsters AL and BR does not significantly increase the stresses on the car.

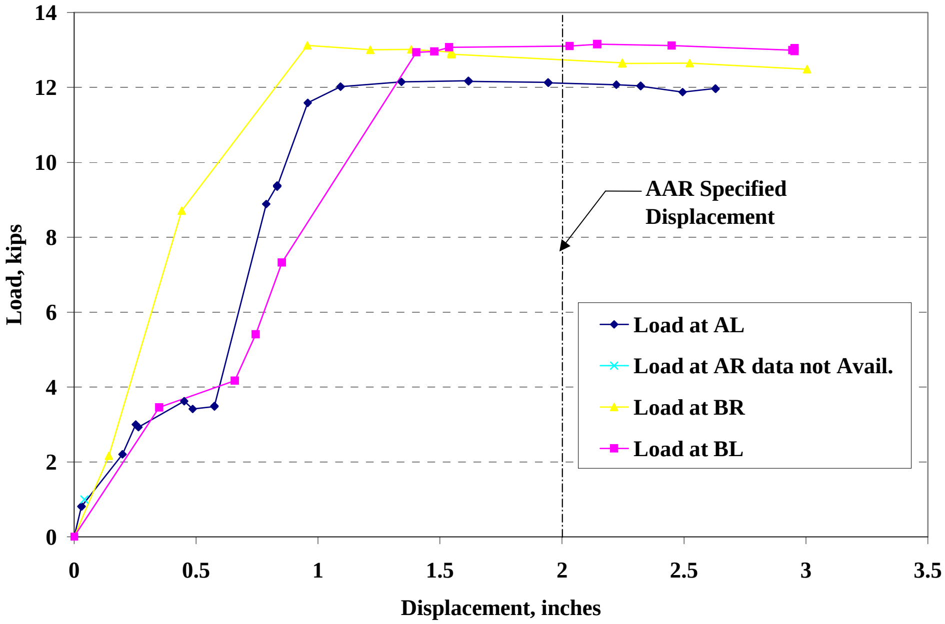

Figure 4.7 Load versus Displacement Behavior for Jacking under the Bolsters of the Empty Bar-Reinforced Tank Car

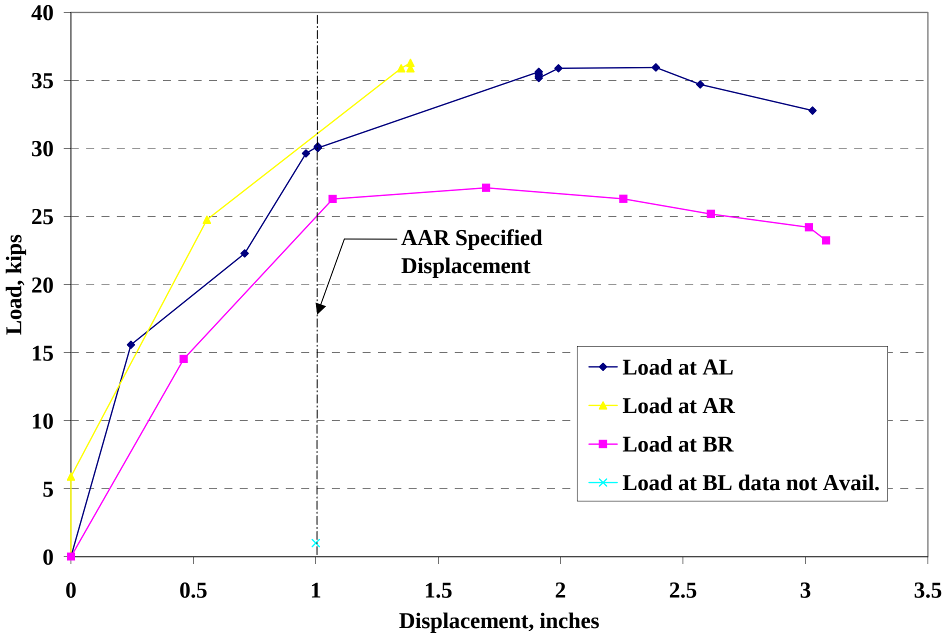

Figure 4.8 Load versus Displacement Behavior for Jacking under the Bolsters of the Full Bar-Reinforced Tank Car

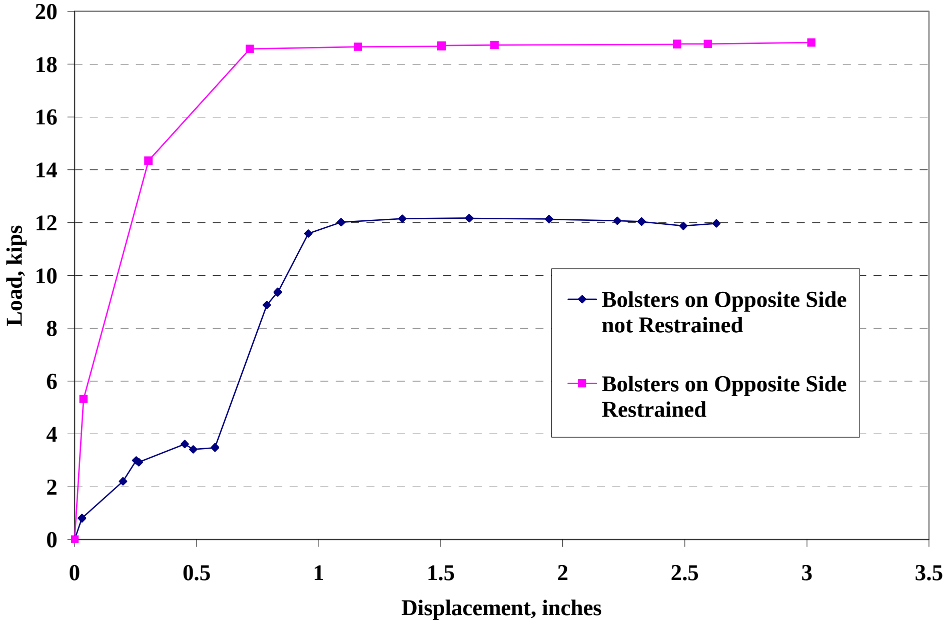

Figure 4.9 Load versus Displacement Behavior for Jacking under Bolster AL with and without Restraining Bolsters on the Opposite Side of the Empty Bar-Reinforced Tank Car

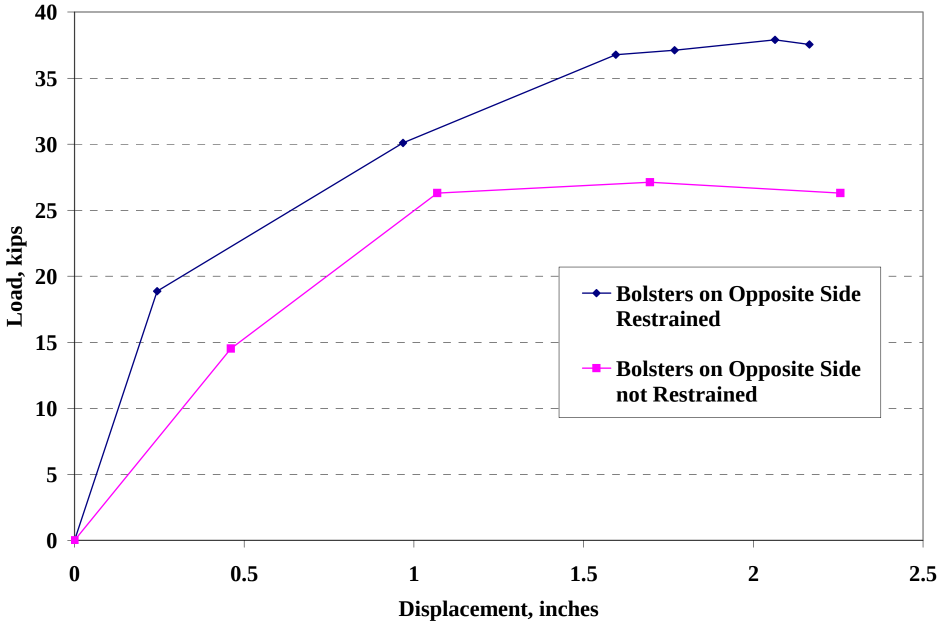

Figure 4.10 Load versus Displacement Behavior for Jacking under Bolster BR with and without Restraining Bolsters on the Opposite Side of the Full Bar-Reinforced Tank Car

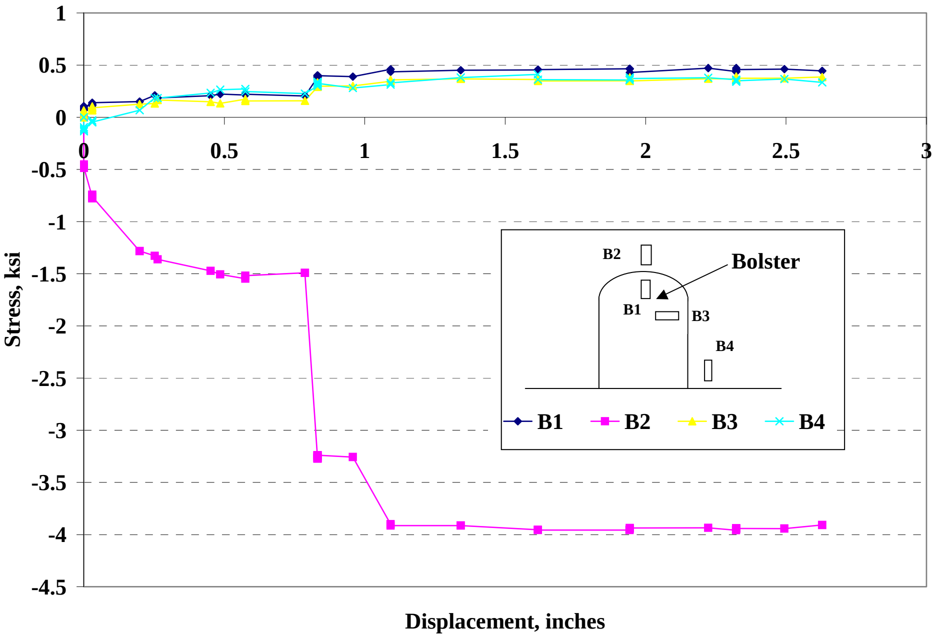

Figure 4.11 Stress Distribution around the Bolster AL when Jacking under Bolster AL for the Empty Bar-Reinforced Tank Car

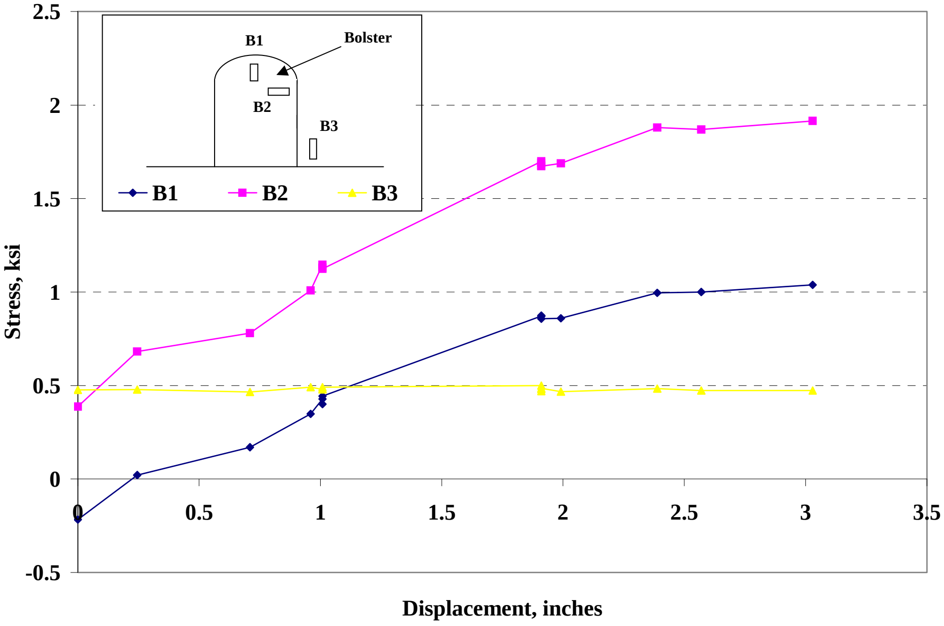

Figure 4.12 Stress Distribution around the Bolster AL when Jacking under Bolster AL for the Full Bar-Reinforced Tank Car

Table 4.2 Empty Car

Table 4.3 Full Car

4.3.7 Stress Conditions from Sill Jacking Tests

Jacking under the sill of the empty car was found to generate high tensile stresses in key areas not stressed by the other loadings. The beneficial effects of jacking under the empty car and results from testing on the full car can be summarized as follows:

1. The reinforcing bars on the bottom shell of the empty car are stressed in tension.
2. The area around the termination of the middle reinforcing bar into the tank shell was found to be in tension when jacking empty. In addition, jacking under the full car results in high tensile stresses in this area.
3. The longitudinal welds inboard of the bolster (SH-T), are stressed on the empty car. This beneficial effect is reduced as we move away from the bolster. This condition occurs on the empty car only.
4. High compressive stresses occur in the headblock region at the end where the vertical load is applied. Table 4.4 provides a summary of the stresses that occur in this region.

Table 4.4 Stresses in the Headblock Region from Sill Jacking Tests

Load Condition	**Stresses in the Headblock Region at End-A[a], (ksi)**					
	HB1	**HB2**	**HB3**	**HB4**	**HB5**	**HB6**
Load at A-End (Empty- 1 in., 21.8 kips)	-6.0	-1.6	-0.7	-1.4	-1.9	-2.2
Load at A-End (Full [b]- 47.8 kips)	-23.4	-4.8	-1.7	-4.7	-6.8	-7.8
Contents	-0.8	0.2	-0.2	0.2	0.0	-0.4

[a] Refer to Figure 4.14 for Strain Gauge Locations
[b] Stresses are inclusive of those caused by the car's contents

4.3.8 Stress Conditions from the Pressure Test

Stress fields produced by the pressure test on this car are consistent, in many areas, with those that occur on the other cars. The pressure test is very effective in stressing tank shell welds and areas around nozzles. Structural differences in this car compared to those in the other cars tested, influence the behavior of this car during the pressure test. The three reinforcing bars on the bottom shell of the car move the centroid of the circular section away from its center towards the bars. The resultant longitudinal force component created during the pressure test acts through this eccentricity. The result is a compressive state of stress in the reinforcing bars. The resultant neutral axis will be above the reinforcing bars and results in low stresses at the level of the re-pad.

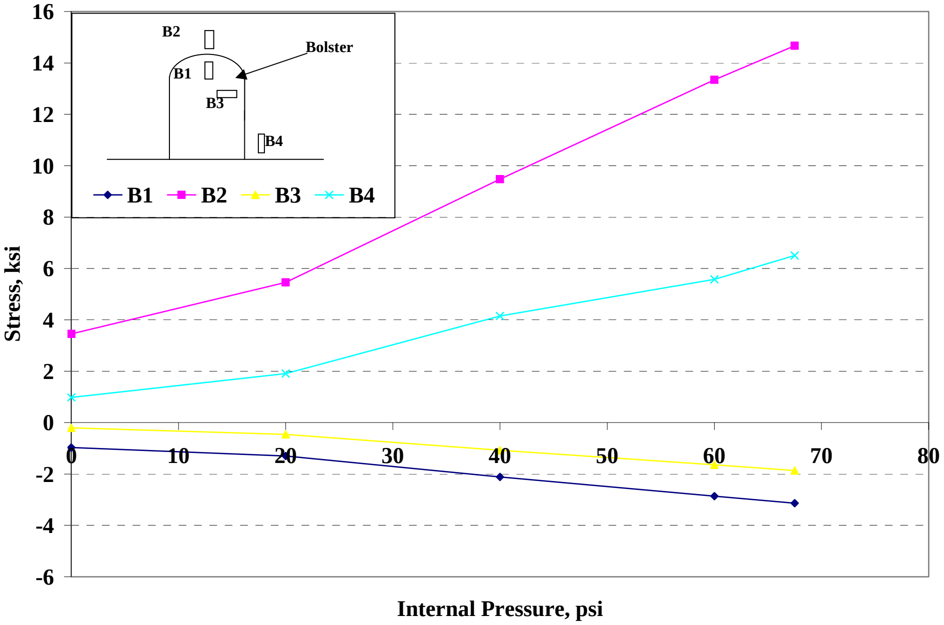

Figure 4.13 Stresses in the Region of Bolster AL of the Bar Reinforced Tank Car for a Pressure Test

High compressive stresses also occur on the bolster pad itself. This is consistent with test results from the other cars. High tensile stresses also occur in the tank shell around the bolster (Figure 4.13).

Stresses from the pressure test in the headblock region are seen in Figure 4.15. The compressive stress in the headblock is most likely due to a confining effect in that area. Welds connecting the headblock to the tank shell are in a state of tensile stress.

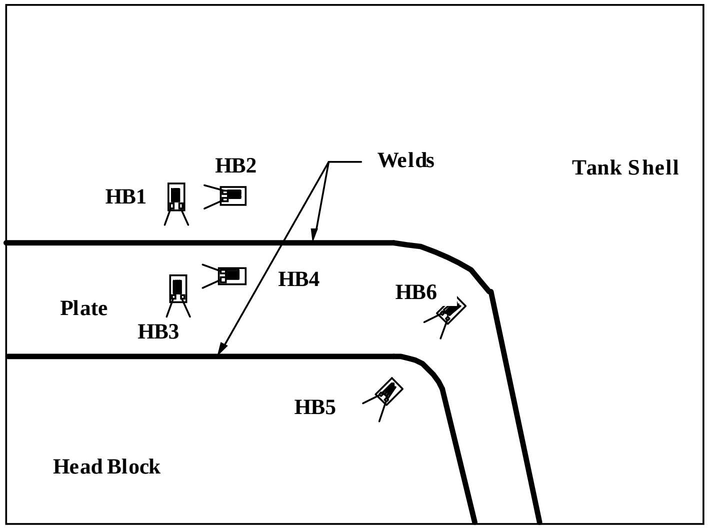

Figure 4.14 Strain Gauge Locations on Bar-Reinforced Car at the Upper Part of the Headblock/Tank Head Junction

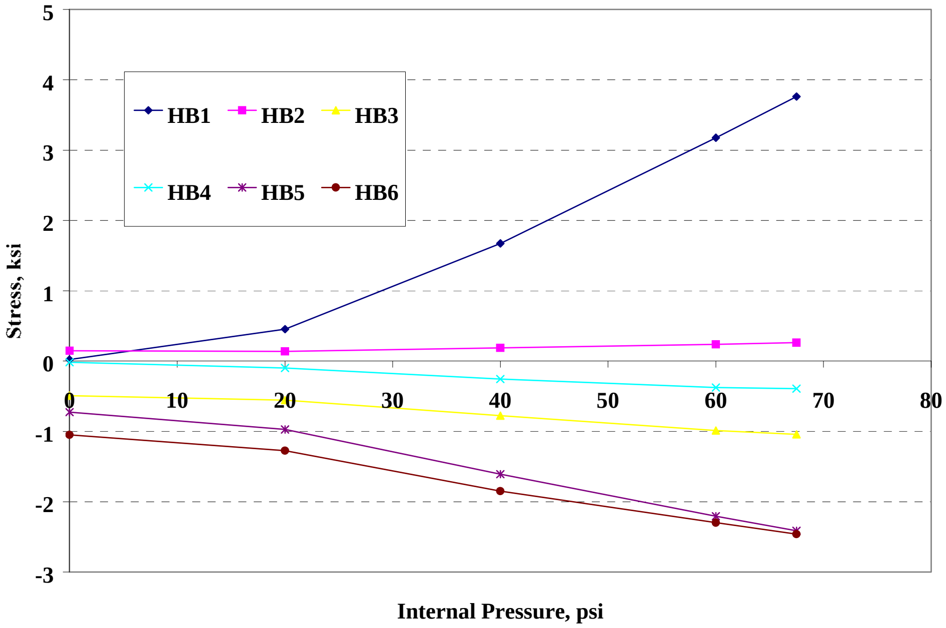

Figure 4.15 Stresses on the Headblock of the Bar-Reinforced Tank Car during a Pressure Test

4.3.9 Stress Conditions from Draft Load Test

There is an inherent difficulty during the draft load test in holding the load on the test car. This is due to the jerking nature of the applied pull and the movement of the tank cars. Acoustic emission testing usually requires a significant period of load hold. The problems of load hold, magnitude of draft load, and noise associated (see section 6.1.5) with this test make application of this technique in its current form unsuitable. However, from this test, it was possible to obtain an indication of the stress field's directionality and magnitude from such a load. From the cross-sectional area of the coupler, it was determined that an approximate force of 26,000 lb. was applied to the car.

Table 4.2 tabulates the stresses produced in key locations from the draft load test. The obtained results confirm expectations of high tensile stresses on the reinforcing bars and around the termination of the middle bar into the tank shell. In addition, the stresses produced tend to quickly diminish as we move towards the top of the car. This is apparent in the low stresses produced near the girth welds (measured at the end of the 4 ft. arc subtended from the bottom longitudinal centerline).

CHAPTER 5

BEHAVIOR OF A PRESSURE TANK CAR UNDER LOADING STIMULI

5.1 INTRODUCTION

This chapter describes a series of experiments conducted on a pressure car. This car design is different from the general purpose car type in that its thickness is significantly larger. The tank car tested was designated as a US DOT-112S400W with a capacity of 24, 302 gallons. ACF Industries built the car in December 1970 (ACAX 80013). The car was non-jacketed and had no bottom attachments. The car was tested at the Rescar service facility in Orange, Texas.

From the few records available on this car, it was determined that the shell thickness was originally 0.7317 in. Over the years, it lost an estimated average of 0.06 in. in thickness due to corrosion. A recent ultrasonic inspection on this car revealed that in some places more material was lost to corrosion (Giffin 1999). The ACF style 200 underframe is fabricated with a standard 41# CZ section center sill and a ½ in. thick by 36 in. wide sill-reinforcing pad. This design was produced from approximately 1967 to 1997. According to the manufacturer, the areas that experience the highest loads are the ends (inboard and outboard) of the Z-sill attachments to the sill reinforcing pad (ACF 1999). The design of this car is also different from the others tested in that it does not have a headblock. It is also different from the general purpose car in that its outlet is located on the top of the car, leaving the bottom free of any outlets.

Standard and modified jacking procedures were conducted on the full and empty car. Experimentation with alternative stressing techniques on this car included the application of vertical loads at the sills and a tensile load on the car through its couplers. The pressure and twist bar tests were also performed.

Figure 5.1 Overall View of Pressure Tank Car

5.2 EXPERIMENTAL PROGRAM

5.2.1 Instrumentation

The instrumentation procedures used on this tank car are similar to those employed on the general purpose car described in Chapter 3. The strain-gauged quadrant of this tank car was the BR quadrant. Strain gauges were placed in areas of potential flaws as discussed in Chapter 3 and as shown in Figure 5.2.

Some design details created accessibility issues and made it difficult to strain gauge certain areas on this car. The area where the head and sill meet could not be instrumented because of the head protection in that area. Linear potentiometers were also used on this car to measure displacements.

5.2.2 Bolster Jacking Tests

The first series of tests conducted on this car involved applying the standard bolster jacking loads (AAR 1999). These loads were applied to the empty and full car. Measurements of load and displacement were made in a manner similar to that described for the other cars tested. Figure 5.3 shows a typical test setup for a bolster jacking test. Load was applied through a roller bearing so as to avoid lateral loads.

Figure 5.2: Detail of Non-Continuous Pad and Bottom Shell of a Pressure Car showing Strain Gauged Locations

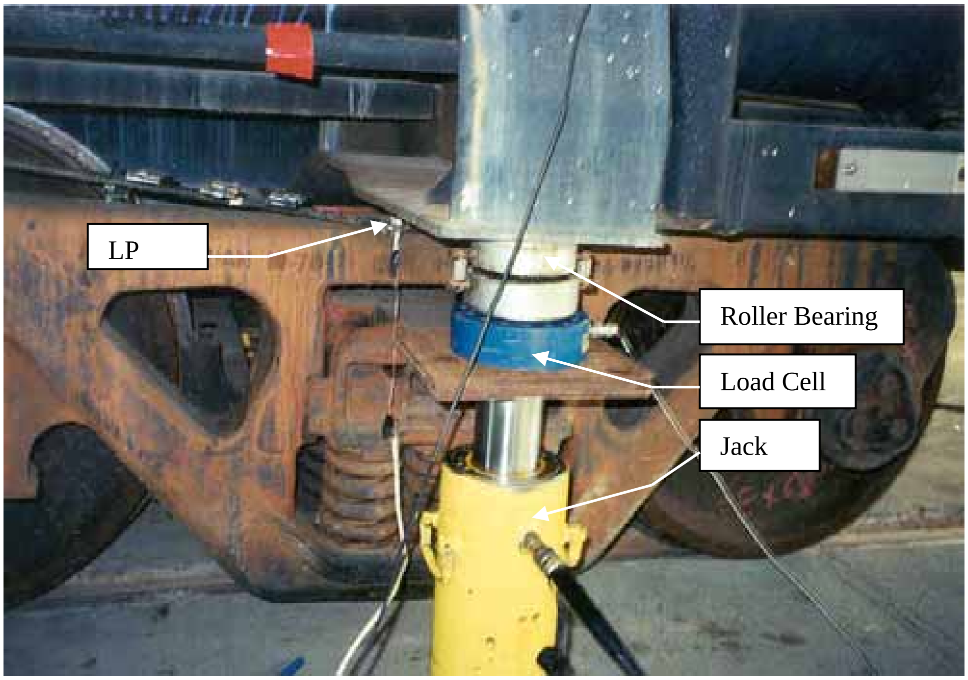

Figure 5.3 Test Setup for Bolster Jacking on the Pressure Car

5.2.3 Restrained Bolster Tests

A variation of the standard bolster jacking procedures was the focus of this set of experiments. The modified procedure involved blocking the movement of the bolsters on the opposite side of the tank car. Figure 5.4 shows a plan view of the tank car identifying the locations where the load was applied and where the bolster movement restrained. It was initially believed that restraining the bolsters would reduce the dependence of the stresses' on the springs. Restraining the bolsters was also believed to help in reducing free play and roll.

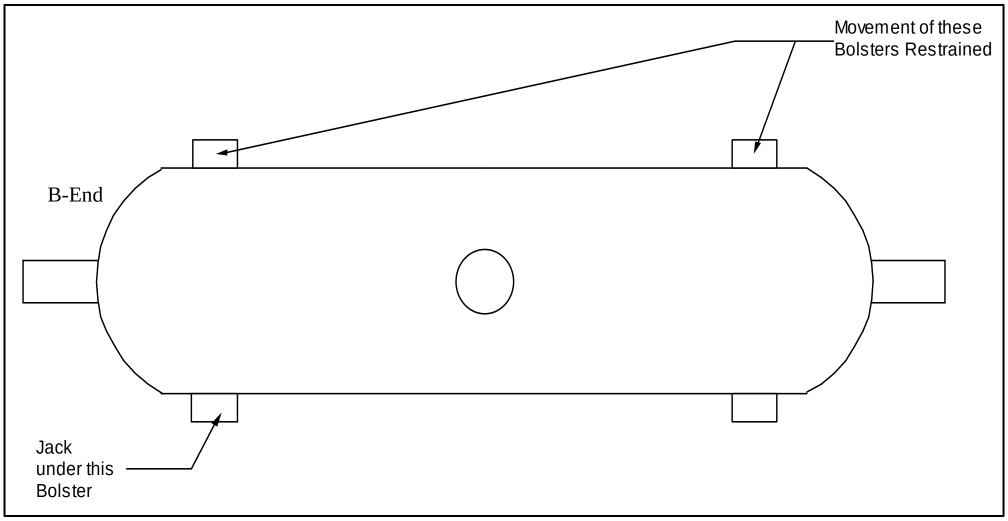

Figure 5.4 Schematic showing the Bolster Jacking Procedure with Restrained Bolsters on the Other Side

5.2.4 Sill Jacking Tests

Jacking under the sill striker plate was performed on the pressure car. The car was lifted to 2 in. when empty and 1 in. when full. The tests were performed on both ends of the car. Load and displacement were measured at the sill striker plate. Figure 5.5 shows the test setup for the sill-jacking procedure.

5.2.5 Sill Twist Tests

Strain gauging the area around the junction of the head and sill was difficult because of lack of accessibility. The twist bar tests were conducted on the full and empty car to determine if beneficial stressing occurs inboard of the bolsters. Figure 5.6 shows the test setup used for the twist bar test.

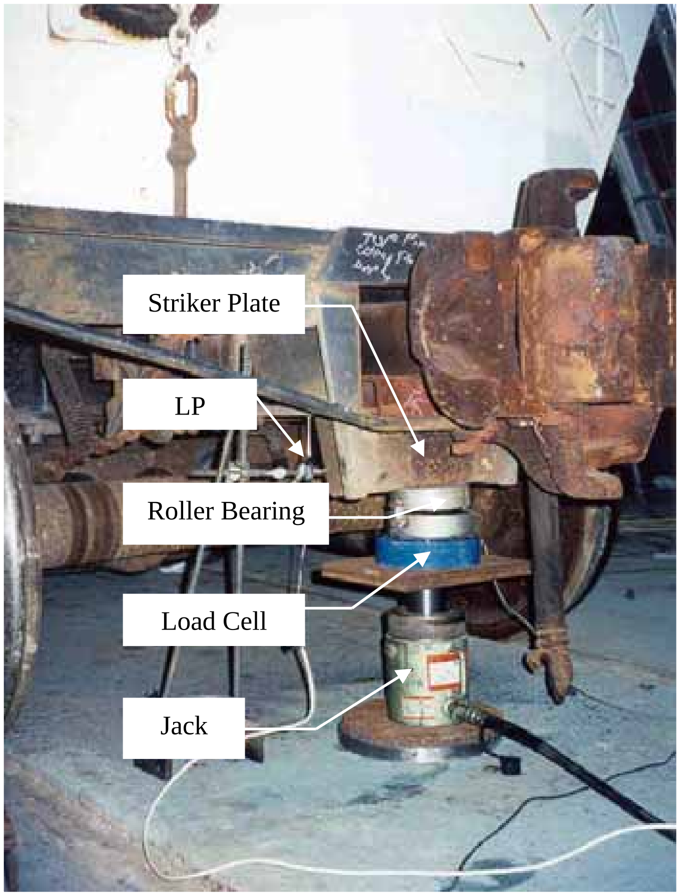

Figure 5.5 Test Setup for Jacking under the Striker Plate of the Pressure Car

5.2.6 Pressure Test

This test involved monitoring the stresses in the car as the internal pressure was gradually increased to reach the pressure specified by the AAR procedure (AAR 1999). The pressure was increased in increments of 20 psi to a maximum pressure of 280 psi. A pressure gauge at the top of the car was used to determine the pressure.

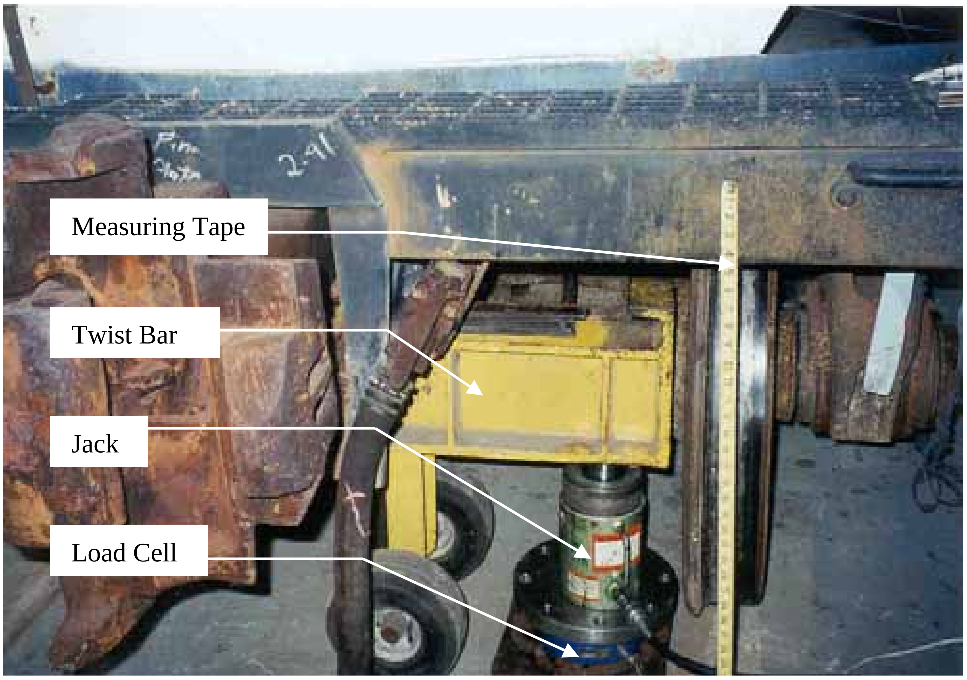

Figure 5.6 Test Setup for the Twist Bar Test on the Pressure Tank Car

5.2.7 Draft Load Test

A tensile load was applied to the car with the help of a switch engine. Three cars with their brakes set were placed on one end of the car, and the switch engine was placed at the other end. The cars on the other end were used to react to the force from the switch engine and induce a tensile load in the car.

The switch engine could not overcome resistance created by the pressure and anchor cars. Strain gauges on the coupler were used to estimate the amount of load applied. An estimated 19,000 lb. was measured at the front coupler. Figure 5.7 shows an overall view of the pressure car pulled by the switch engine.

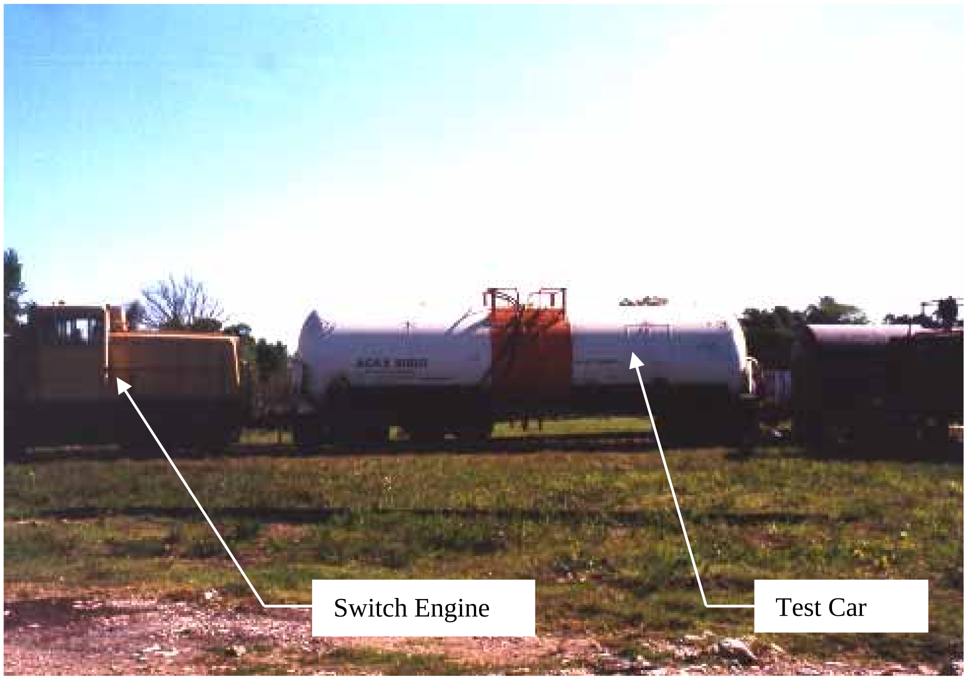

Figure 5.7 Switch Engine Pulling on the Pressure Car

5.3 TEST RESULTS FOR THE PRESSURE TANK CAR

5.3.1 Load Displacement Behavior for Bolster Jacking Tests

Figure 5.8 shows the displacements of the bolsters when jacking under bolster BL of the empty car. The load was measured under bolster BL. The maximum load is attained at a displacement close to 2 in. For the full car, displacement beyond 1 in. will result in increasing load applied to the car (Figure 5.9).

Figure 5.10 shows the load-displacement behavior from four separate tests on the empty car when jacking independently under the four bolsters. The maximum load reached from these tests is within acceptable limits for the 2-in. AAR specified displacement.

There is less variation in the load-displacement behavior of the full car to the bolster jacking tests. The curves are linear up to and beyond the currently specified displacement (Figure 5.11). After lifting the bolsters above 1 in. the load continues to increase even until the maximum applied deflection of 2 in. Increasing the displacement beyond 1 in. will result in increasing the stresses in the tank car. However, the rate at which the stress varies with the applied load is dependant on the location. As will be shortly discussed, the influence of the contents cannot be considered insignificant during AE testing on a full car.

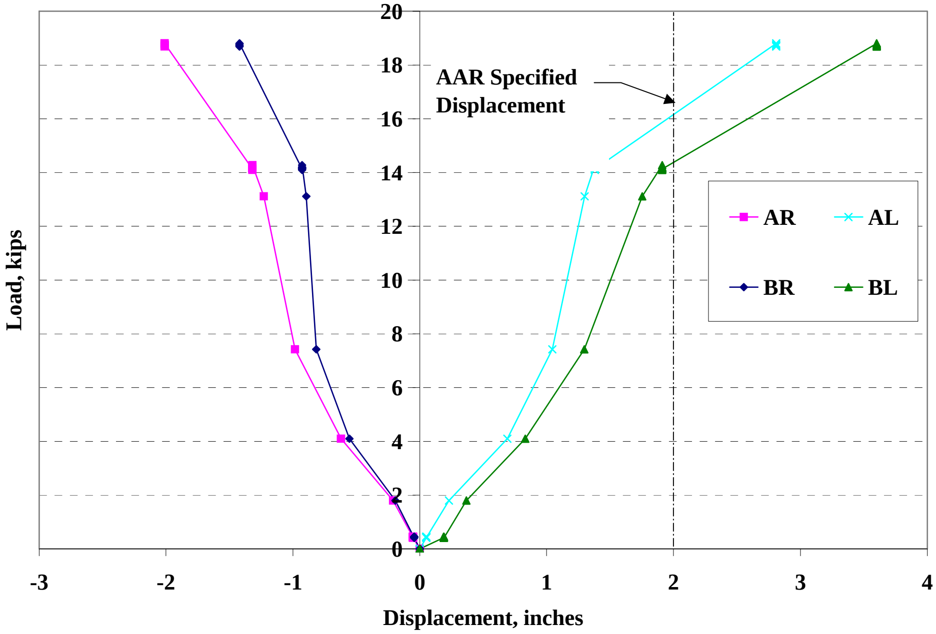

Figure 5.8 Bolster Displacements when Jacking under Bolster BL of the Empty Pressure Car

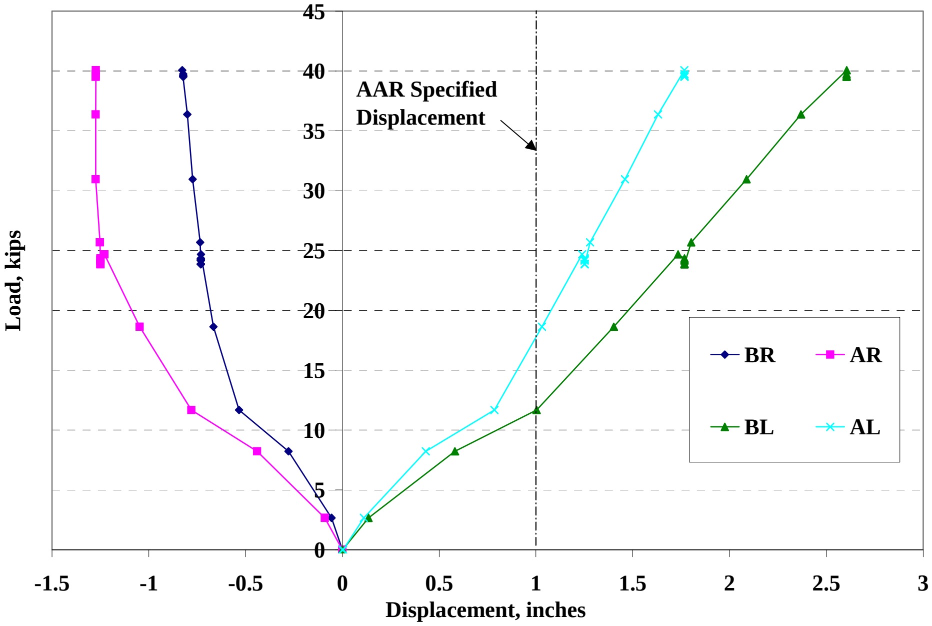

Figure 5.9 Bolster Displacements when Jacking under Bolster BL of the Full Pressure Tank Car

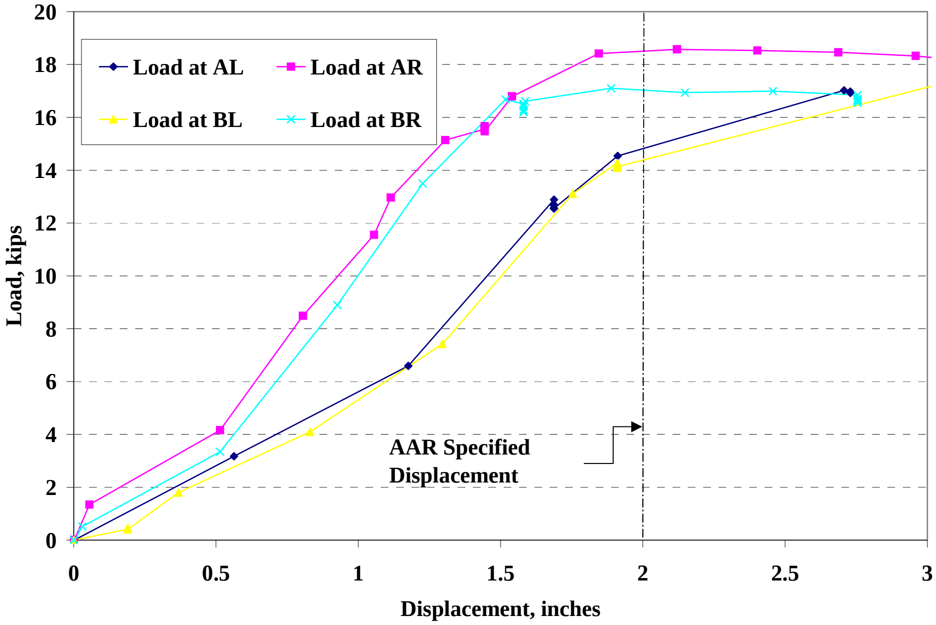

Figure 5.10 Load versus Displacement Behavior for Jacking under the Bolsters of the Empty Pressure Car

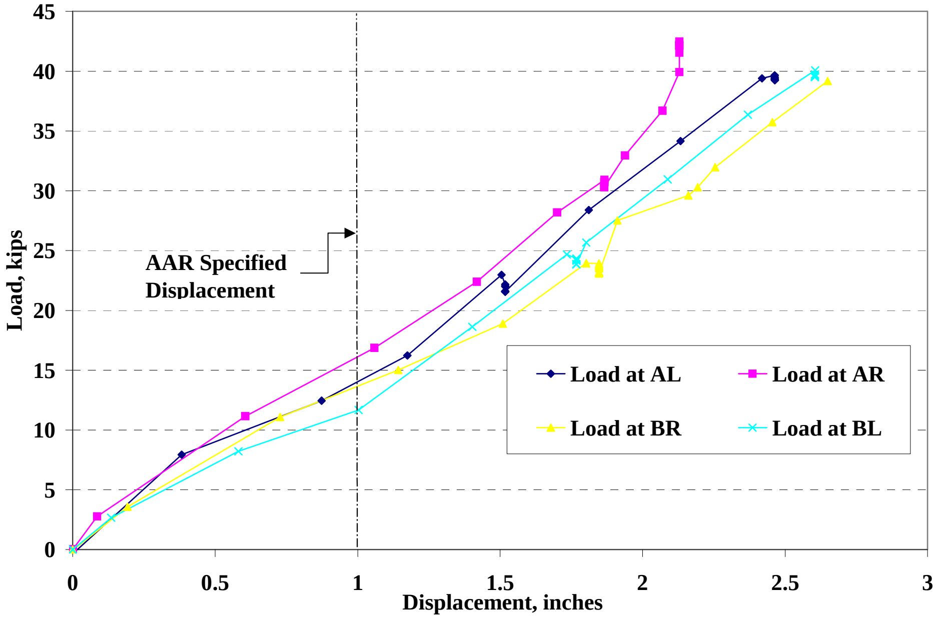

Figure 5.11 Load versus Displacement Behavior for Bolster Jacking under the Bolsters of the Full Pressure Car

5.3.2 Load Displacement Behavior from Restrained Bolster Tests

The process of restraining the bolsters on the other side of the car during the jacking process results in additional load being applied to the car. Figure 5.12 shows a comparison of the load-displacement behavior for restrained and unrestrained cases on the empty car. Note that the maximum load occurs after 1.5 in. of deflection for both tests. The applied load is nearly doubled from the restraining process. A similar behavior is observed on the full car (Figure 5.13).

Monitoring of the displacements on the jacking side reveals large movements on the un-jacked bolster (Figure 5.14 and Figure 5.15). This suggests that roll still dominates the behavior of the car despite of restraining the bolsters on the other side of the car.

5.3.3 Load-Displacement Behavior from Sill Jacking Tests

Jacking under the sill striker plate of the general purpose car was found to be effective in stressing some key areas. These tests were repeated on this car with similar results. Figure 5.16 and Figure 5.17 show the load-displacement behavior when jacking under the sill striker plate for the empty and full car.

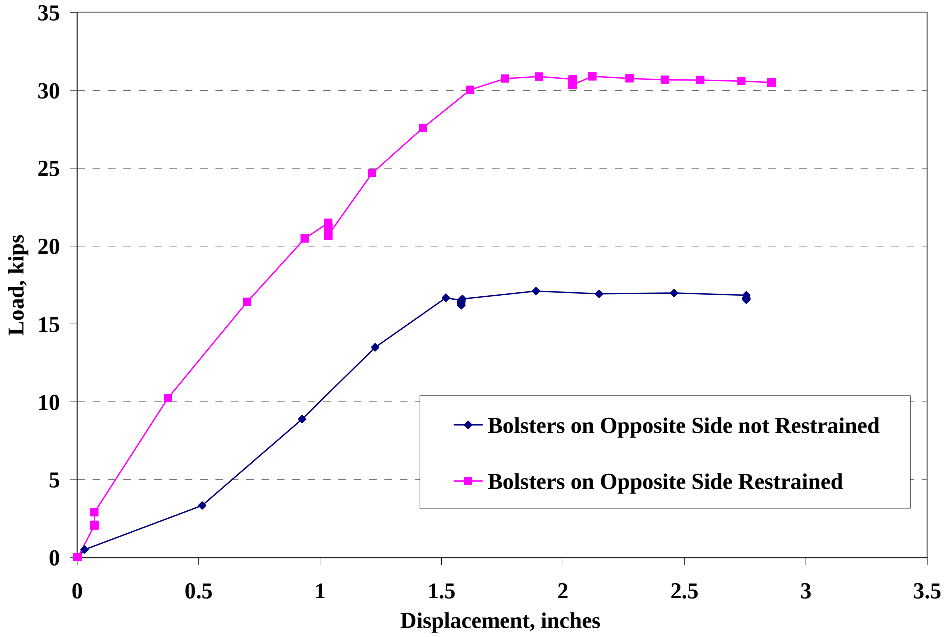

Figure 5.12 Load versus Displacement Behavior for Jacking under Bolster BR with and without Restraining Blocks on the Opposite Side of the Empty Pressure Car

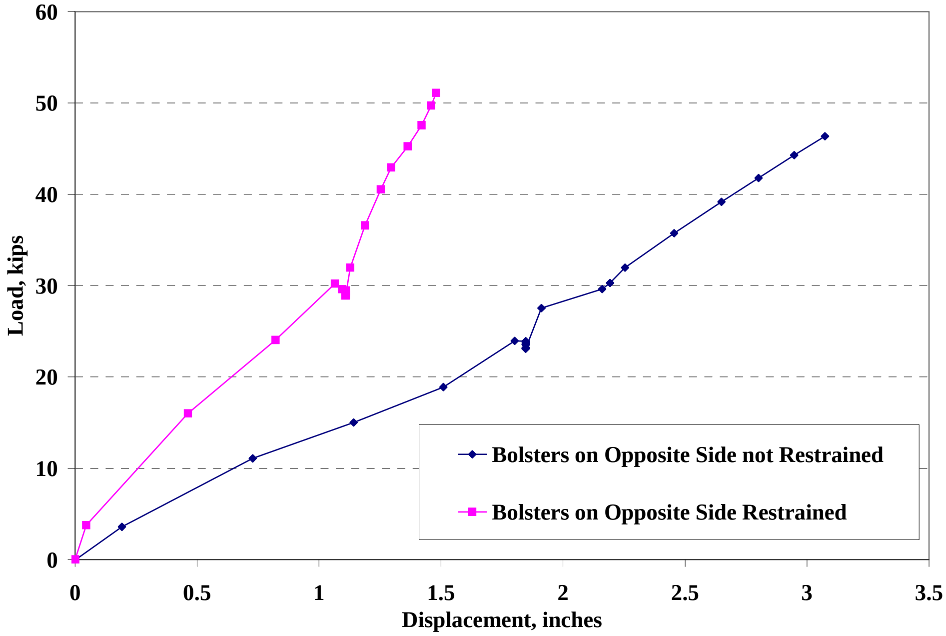

Figure 5.13 Load versus Displacement Behavior for Jacking under Bolster BR with and without Restraining Blocks on the Opposite Side for the Full Pressure Car

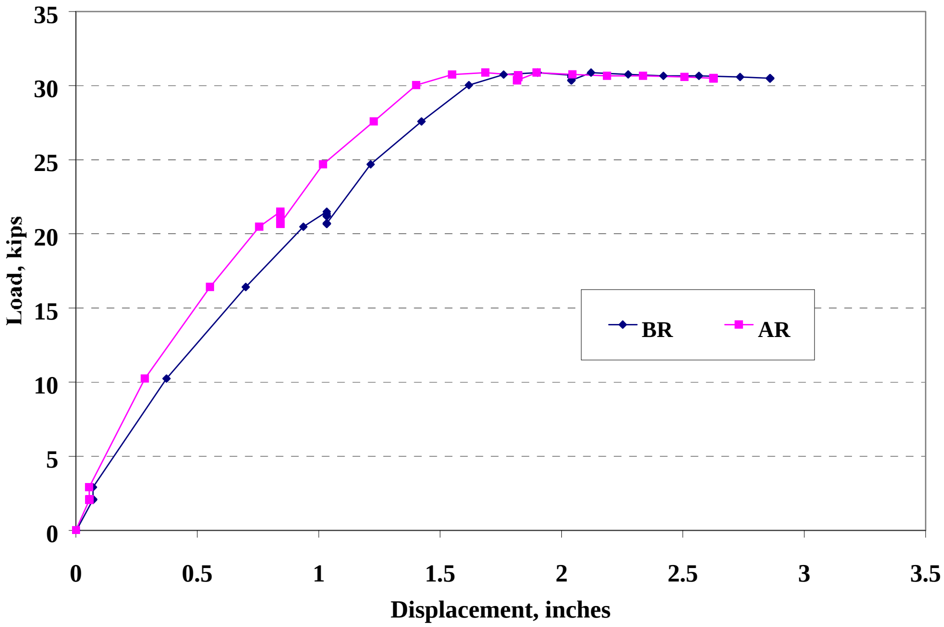

Figure 5.14 Bolster Displacements during the Restrained Bolster Test on the Empty Car, Load at BR

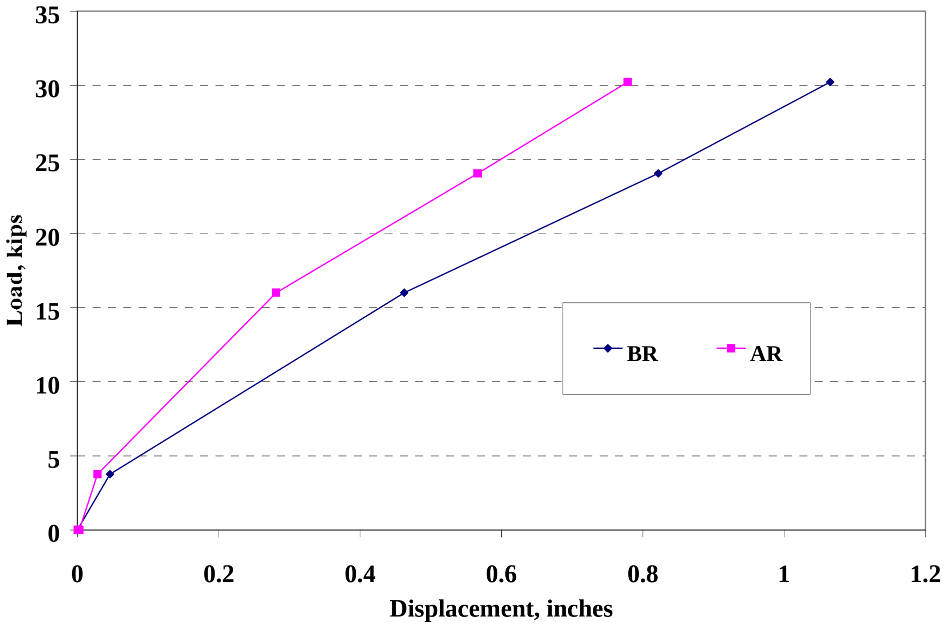

Figure 5.15 Bolster Displacements during the Restrained Bolster Test on the Full Car, Load at BR

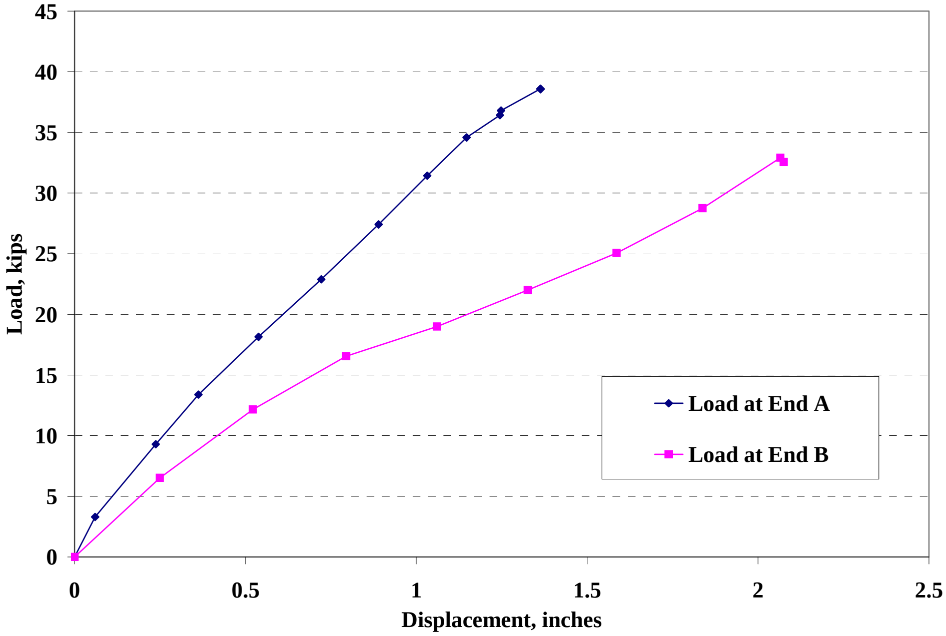

Figure 5.16 Jacking Load versus Displacement Behavior when Jacking under the Sill Striker Plate of the Empty Pressure Car

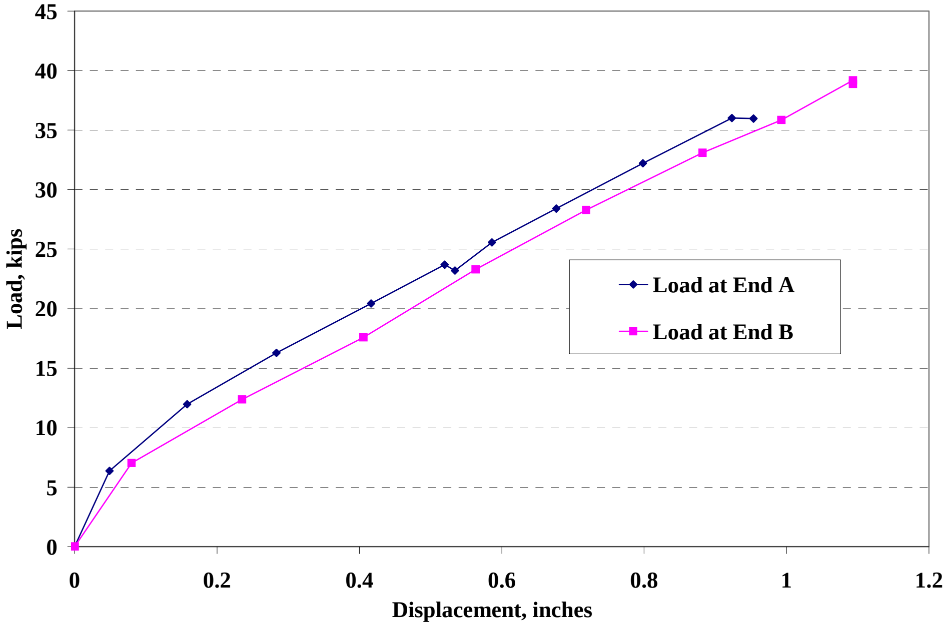

Figure 5.17 Jacking Load versus Displacement Behavior when Jacking under the Sill Striker Plate of the Full Pressure Car

5.3.4 Effect of Tank Car Contents on Stress Conditions

The pressure car experiences stress conditions from the contents similar to those occurring on the general purpose car. The magnitudes of these stresses are lower in this car due to its larger wall thickness. Table 5.1 shows stress values in different areas due to the load from its contents.

Table 5.1 Stresses in Key Areas from Tank Car Contents

Area	Longitudinal re-pad weld (TS-2)	Inboard sill web (SL-1)	Inboard sill termination into re-pad (SL-2)
Stress (ksi)	0.2	-0.2	-1.2

5.3.5 Stress Conditions from Bolster Jacking Tests

Jacking under the bolsters of this car for a given displacement causes stress conditions very similar to those that occur on the other cars tested in this research, given the same conditions. Figure 5.18 shows the stresses near bolster BR as the empty car is lifted. Compressive stresses are seen to occur at the bolster where the jacking is being performed. Table 5.2 shows a summary of stresses around the jacking bolster from different tests.

Filling the tank car with water alters the response of the tank car to the applied loads. The weight of the contents themselves causes stresses that are on the order of the stresses caused by the applied loads. Small tensile stresses are produced around the bolster when it is full (Figure 5.19). During bolster jacking on a full car, compressive stresses also occur around the jacking bolster. A summary of these and other observed stresses from all the tests performed are shown in Tables 5.3 and 5.4

Table 5.2 Average Opening Stresses Around Jacking Bolster BR

Load Condition	**Stresses in Key Areas (ksi)** [a]				
	Lower left of bolster	Upper left of bolster	Top of bolster	Lower right of bolster	Upper right of bolster
2 in. displacement on empty car	-0.4	-2.4	-3.0	-0.7	-2.7
2 in. displacement + dead weight of water	0.0	-3.5	-5.9	-0.4	-3.2
Dead weight of water	0.8	1.9	0.2	0.7	1.0

[a] Bolster stresses are in the vicinity of bolster BR and are on the tank car shell.

5.3.6 Stress Conditions from Restrained Bolster Tests

Restraining the bolsters on the other side of where the jacking was performed increases the load applied. However, there are only marginal improvements in the effectively stressing new areas. The additional load seems to concentrate its effect in the region around the bolster. This results in about a two-fold increase in compressive stresses in that region. Other monitored areas of the tank car do not experience significantly higher stresses.

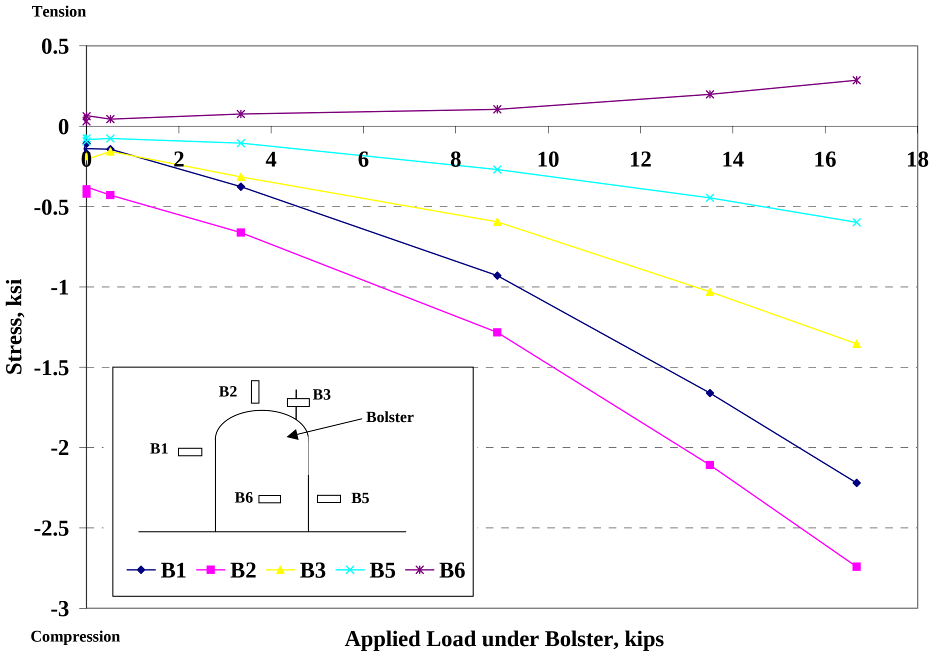

Figure 5.18 Stresses around the Bolster when Jacking under Bolster BR of the Empty Pressure Car

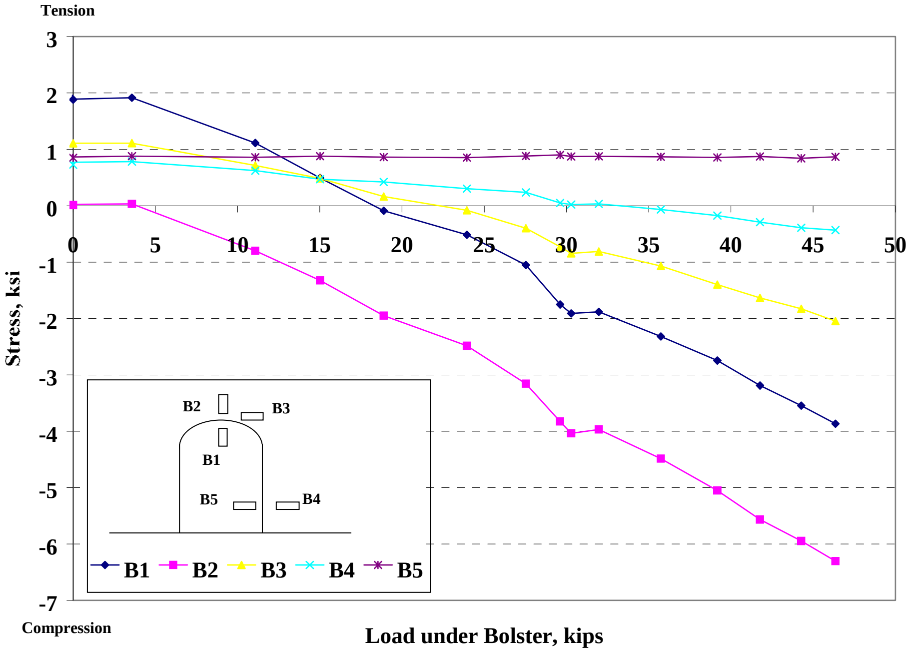

Figure 5.19 Stresses around the Bolster when Jacking under Bolster BR of the Full Pressure Car

Table 5.3 Summary on Empty Car

Table 5.4 Summary of Full Car Stresses

5.3.7 Stress Conditions from Sill Jacking Tests

Jacking under the sill of this car was found to produce beneficial tensile stresses at the location where the sill-reinforcing pad terminates inboard into the shell of the tank car (Figure 5.20). The stress in the empty car perpendicular to this transverse weld was 1.5 ksi while the stress in the sill-reinforcing pad was close to 0.5 ksi. Conducting this test on the full car also yields favorable behavior in this location. A tensile stress of about 4.9 ksi was achieved in the tank shell for a displacement of 2 in. at the striker plate.

Figure 5.20 Strain Gauge Rosettes at the Termination of the Sill Reinforcing Pad into the Shell of the Pressure Car

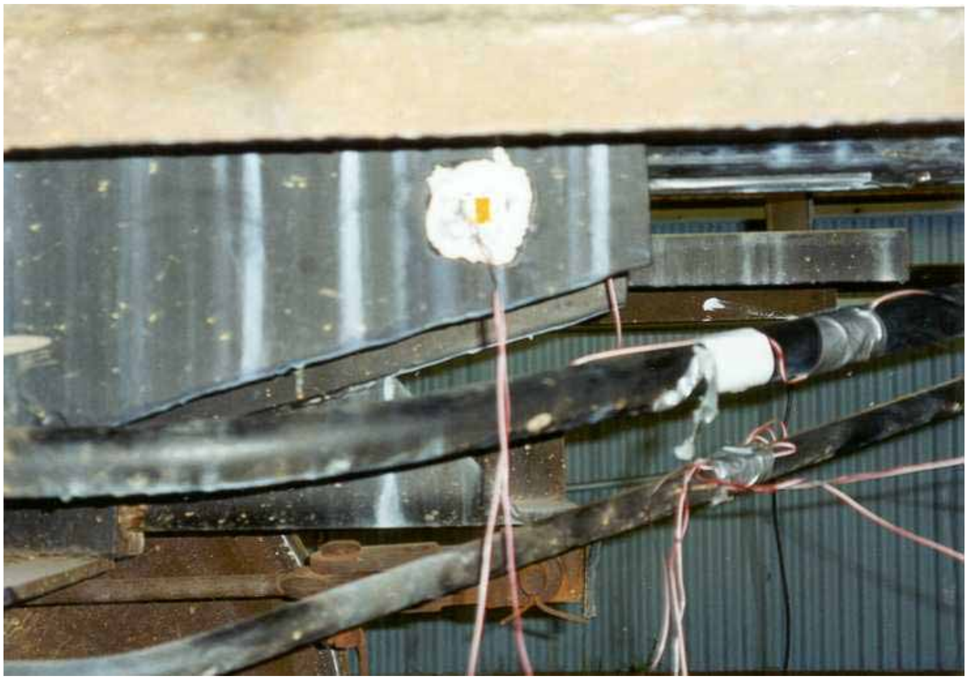

Figure 5.21 Strain Gauging of the Sill as it terminates into the Sill Reinforcing Pad of the Pressure Car

The web of the sill and the area around its inboard termination into the sill re-pad undergoes a considerable tensile stress on the empty car (Figure 5.21). There is also some stressing of the longitudinal inboard sill re-pad to tank shell welds on the empty car. Testing on the full car does not result in beneficial stresses in this area. Table 5.3 and 5.4 shows the stresses in key areas stressed by this procedure.

5.3.8 Stress Conditions from Sill Twist Tests

Accessibility issues made determining the stresses due to the twist bar test difficult in the region where the head and sill meet. An examination of the stresses in the car reveals, that tension occurs near the bolsters, but the effect soon disappears as we move towards the horns. Tensile stresses believed to occur from the lift component of the twist-bar test occur in some locations inboard of the bolsters as identified in the previous section. The magnitudes of these stresses are lower than those that occur from jacking under the sill.

5.3.9 Stress Conditions from the Pressure Test

A pressure test was conducted on this car as specified by the AAR procedure (AAR 1999). Figure 5.22 shows a plot of the stresses near bolster BR as the pressure was increased. It is apparent that the stresses created by the pressure test are much larger than those that occur from bolster jacking tests. This is particularly true for the pressure car. The ratio of wall thickness to applied pressure is lower on a pressure car compared to a non-pressure car. One of the stresses, not shown in Figure 5.22, is the stress that occurs on the bolster pad (B6 in Figure 5.22). It was observed that a compressive stress on the pad of 3.8 ksi occurs at an internal pressure of 280 psi. The pressure test, although effective in generating high tensile stresses in the tank shell, results in other areas of the car experiencing low stresses.

Applying an internal pressure to this car was found to effectively create high stresses in the car shell. Structural attachments such as the sill do not get stressed well from this test. The main observations from the pressure test can be summarized as follows:

1. The stresses at the location where the sill re-pad terminates into the car reach tensile stresses on the order of 12.4 ksi at the maximum internal pressure of 280 psi (Figure 5.22).
2. The welds that run in the longitudinal direction joining the sill re-pad to the tank shell experience high tensile stresses. In one location inboard of the bolster, the stress in the hoop direction (or transverse to these welds) was found to be 26.7 ksi.
3. The car's contents cause the sill's web inboard of the bolster to go into compression (Figure 5.21). Pressurizing the car does not create significant stresses in this area.
4. The inboard transverse sill to re-pad welds are also under a high compressive stress from the contents. Pressurizing the car does not create significant stresses in this area.

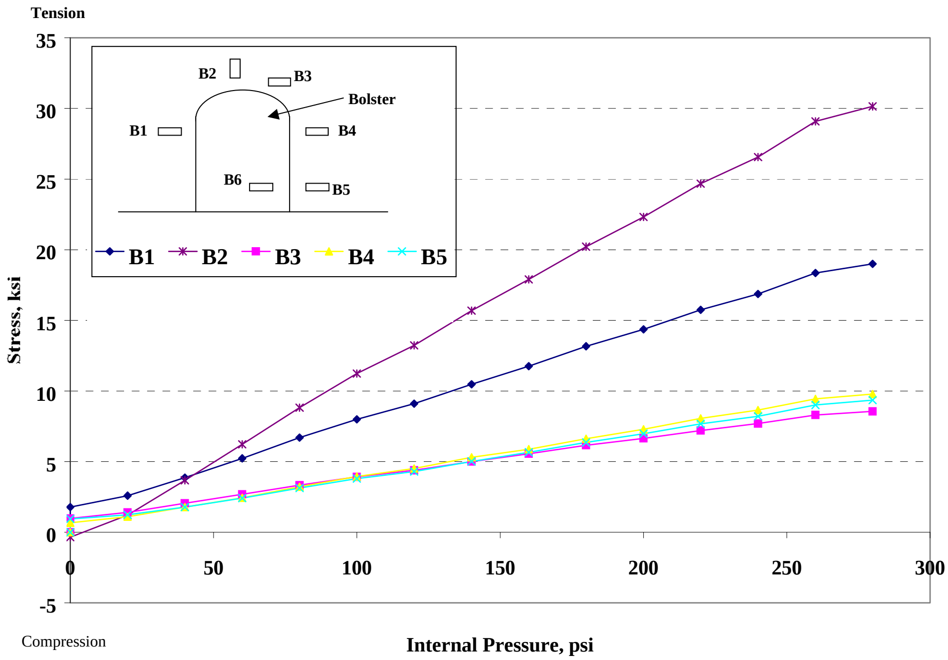

Figure 5.22 Stresses near the Bolster of the Pressure Car During a Pressure Test

5.3.10 Stress Conditions from the Draft Load Test

Railroad tank cars are designed for high draft loads (usually 1.5 million lb.). The limited amount of tensile load applied (19,000 lb.) provides an indication of the stress directionality and magnitude in the car created by a tensile load. Table 5.3 provides a summary of the stresses in the areas monitored. Based on the acquired data, the areas that will most likely benefit from an increased tensile load are:

1. The transverse welds attaching the sill re-pad to the car.
2. The transverse welds attaching the sill to the re-pad.

3. The longitudinal welds attaching the sill to the re-pad.

The sill jacking procedure stresses the areas described in the first two items above. However, the magnitude of theses stresses is dependant on the weight of the car. The draft load test with the aid of a special test frame can be designed to increase the stress magnitudes in these areas.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

This study obtained strains and load-displacement measurements from load tests on three different car types. The first car tested was a non-jacketed general purpose car with no heavy bottom attachments. The second was a non-jacketed general purpose car with continuous bottom attachments, while the third car was a non-jacketed pressure car with no bottom attachments. These cars were subjected to the loads given by the AAR procedures for AE testing of railroad tank cars (AAR 1999). Experimentation with alternative stressing techniques has provided mixed results. The effectiveness of restraining the bolsters during a jacking test and combinations of jacking loads were evaluated. Limitations and advantages of the pressure and bolster jacking tests in stressing different cars have also been identified. The effect of the car's contents on the stresses was found to be an important factor.

Jacking under the sill striker of a tank car has been shown to give favorable results in stressing key areas in the sill, its inboard termination into the re-pad, and the re-pad's termination into the shell. Reinforcing bars on the bar-reinforced car also benefited from this procedure. In addition, a "pull" or a tensile load was applied on the pressure and bar-reinforced cars. Practical considerations and other factors do not indicate this procedure’s suitability for AE testing on tank cars. However, the behavior of a tank car to a tensile load is now better understood.

A suite of several stressing techniques has been identified and can be utilized for the inspection of the bottom (8-ft arc) area of a railroad tank car. The main stressing techniques recommended are the vertical lifts at the stub sill striker plates, jacking under the bolsters and the twist bar tests. Areas in that envelope that are not stressed by these loads need to be inspected with alternative nondestructive testing procedures (e.g. the bottom center outlet). Issues related to loading and conclusions on the major stressing techniques are presented in the following sections.

6.1.1 Load or Displacement Control

Experimental results clearly demonstrate that the load applied by jacking the tank car is directly related to the stress condition on the car. The difficulty with load control is the non-linear behavior of many of the loading techniques. A positive slope followed by a constant horizontal slope characterizes the load-displacement behavior. This means that after a certain displacement the load ceases to increase with increasing displacement. For other loading conditions, namely jacking on a full car and the twist bar tests, the load continues to increase beyond the test displacement range. Due to the variation in the design and weight of the different cars, displacement control is the most appropriate measure of specifying a jacking load to a car.

6.1.2 Bolster Jacking Tests

There are clearly many differences in behavior during bolster jacking tests on empty and full tank cars. It is recommended to test on empty cars to avoid the high stress in many areas caused by the contents. The restrained bolster tests did not prove to be more effective in inducing favorable stresses on the tested cars.

6.1.3 Sill Jacking Tests

It was found that applying a vertical load at the sill striker plate at each end of the tank car is an effective method of stressing key areas. The lift component in a twist-bar test stresses some of the same areas stressed by this procedure. The magnitude of the stresses produced is significantly greater from sill jacking because of the larger vertical displacement applied. Longitudinal welds attaching the sill re-pad to the tank shell experience tensile stresses. It is not clear however, if these stresses are adequate for AE testing. The area of the inboard sill termination into the re-pad and the re-pad's termination into the tank shell are areas that experience significant tensile stresses. The reinforcing bar on the bar-reinforced car also experiences tensile stresses. The area around the inboard termination of the middle-bar into the tank shell is an area of particularly high stress. The longitudinal welds that attach these bars to the tank car do not experience significant stressing. High compressive stresses in the headblock region may also complement the twist-bar procedure and improve the defect detection in that area.

6.1.4 Pressure Tests and Stressing Procedures

Application of an internal pressure to a tank car is very effective in stressing tank girth welds, tank longitudinal welds and areas around nozzles. Its performance in these areas is unmatched by any of the other techniques discussed. However, this test has many limitations, namely its inability to stress several important areas. The sill and its termination into the re-pad are the main areas that are not stressed well. Tank cars with a longitudinally reinforced bottom have a number of areas that are not stressed by this loading (Chapter 4).

6.1.5 Draft Load Test

A tensile or draft load was applied on the bar-reinforced and pressure cars. The maximum load that could be applied was limited by the weight of the anchor cars in one instance and the capacity of the switch engine in another. The applied load is transitional due to the jerking nature of the load applied by the switch engine. Additional research conducted by the author and not reported in this thesis indicates that large amounts of extraneous noise occur during a draft load test. Acoustic emission monitoring using 150 kHz sensors resulted in AE signals indicative of sliding characteristics with amplitudes as high as 70 dB. For such a test to be made practical, issues of load hold and magnitudes of the applied load need to be resolved. Increasing the applied load in a practical manner may make this a more effective procedure. The maximum load that can be applied by the jacking forces (although affected by the stiffness of the springs and the rolling motion of the car) is ultimately controlled by the car's weight. Ideally, a special test frame may be designed to impart high forces on a tank car and resolve the issues of load hold. However, this is expensive and because it would not be portable, limits the value of the test for general testing.

6.2 SUGGESTIONS FOR FUTURE RESEARCH

6.2.1 Acoustic Emission from Fatigue Cracks

A better understanding is needed of the conditions necessary for the acoustic emission event emitted from a stressed fatigue crack. Most of the fatigue cracks that exist in a tank car are not mode I cracks subjected to a uniaxial stress field. The stress fields generated from the applied loads create a more complex stress field around the location of a possible fatigue crack. It is important for future research to be able to differentiate the proportion of the acoustic emission signals caused by the plastic deformation, crack face rubbing or sliding, and study the corresponding stress fields.

The 10 percent stress criterion used as a basis for determining the suitability of a stressing technique needs to be evaluated to determine whether compressive stresses of the same magnitude can also be used for qualifying a certain test procedure. Clearly, limited laboratory test data and test results from the use of acoustic emission testing in the field have resulted in the detection of cracks in areas where compressive stresses are now known to occur (Section 3.3.5).

6.2.2 Tank Car Defect Database

Areas were defects are likely to occur on a tank car were identified early in the test program. Strain gauging of the tank cars was conducted to determine the stresses in the vicinity of these areas. Identification of these areas was an important prerequisite to all the testing that followed on the general purpose, bar-reinforced and pressure cars. These areas were identified based on consultations with individuals involved in this industry. No account was taken into the frequency of a defect's occurrence. It would not be very beneficial to use a stressing procedure if the likelihood of the defect's occurrence in the stressed area is extremely low. Establishing a database of all the areas where defects are likely to occur and their frequency of occurrence will help in further refining and optimizing the AE stressing procedures.

6.2.3 Finite Element Models

This experimental investigation did not determine the local stresses at the welds (areas where fatigue cracks usually occur). Stresses were determined where strain gauges were located. Judgment may be based on these stresses, provided it is understood that higher stresses are obtained closer to the geometric discontinuity (weld) or fatigue crack. It is also important to realize that areas of complex stress fields occur in many areas and the stresses obtained from the strain gauges may not be representative of the true stress field. Furthermore, a fatigue crack may significantly change the stress field in its vicinity. A more complete evaluation will be possible if finite element models of representative tank cars are developed. From these models, it will then be possible to obtain a better understanding of local stresses in areas where defects are likely to occur. The current AAR procedure requirement on finite element analysis does not clearly specify the areas where the stresses are to be determined (AAR 1999). The expanded finite element model must be capable of determining the local stress at areas of importance. These models will have to take into account complex geometries, boundary conditions and loading effects.

6.3 SUMMARY OF SIGNIFICANT FINDINGS

The results presented in the previous chapters focused on each tank car individually. The following list presents a summary of the major findings that apply to the all the cars in this study:

i. Displacement control is the preferred method for specifying the test loads for the bolster jacking, sill jacking, and twist bar tests.
ii. Tests should be performed on an empty car.
iii. None of the stressing techniques evaluated adequately ensures that the center bottom outlet is inspected.

iv. In general, the current AAR procedure is correct with recognized limitations. However, the current procedure does not always assure a complete inspection.

v. The proposed procedure will lead to improved inspection of the sill and pad attachment welds inboard of the bolsters.

vi. It is recommended that the bolsters on the side of the car, opposite the bolster jacking load remain free.

vii. The study indicates that a compressive stress produces emission from defects. Additional investigation is needed as outlined in section 6.2.1.

viii. A draft load test (coupler pull) has shown limited benefits. It may be difficult to implement in practice and is not recommended.

ix. The sill lift test is capable of stressing many areas as outlined in sections 3.3.6, 4.3.7, and 5.3.7. A preliminary recommendation for the height of lift at both ends of the empty car at the sill striker is 2 in. This recommendation is subject to field qualification tests.

x. The sill lift test is more effective on empty cars than full cars for stressing longitudinal sill re-pad welds inboard of the bolster.

xi. The AAR (1999) procedure was originally developed for general purpose cars. However, this research shows that acoustic emission procedures can be applied to pressure cars.

6.4 RECOMMENDATIONS

The pressure test is not required for the areas of interest covered by CFR title 49, part 180.509 (Federal 1995). The tests described below can be used for the structural integrity inspection of railroad tank cars.

The results of this study indicate that the original objective of developing an alternative AE test procedure to comply with CFR title 49, part 180.509 (Federal 1995) can be achieved with a combination of several tests on an empty tank car. Unstressed areas will need alternative NDT methods and areas not covered by this study will need further examination. The principal recommendations of this study are as follows:

i. Develop a new procedure for the areas of interest covered by CFR title 49, part 180.509. The tests recommended for incorporation into this procedure are:
    a. The twist bar test according to annex Z of the AAR procedure (AAR 1999).
    b. A modification of the current AAR bolster jacking test to include all four corners.
    c. A sill lift test at each end of the car as described in this thesis.

ii. Conduct field tests on a range of railroad tank cars with the new AE procedure to determine its practicality and effectiveness.

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