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STRAIN ANALYSIS OF HMMWV FRONT LIFT PROVISION

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ABSTRACT

The High Mobility Multipurpose Wheeled Vehicle (HMMWV) is equipped with two front lifting provisions which support the vehicle during external airlift operations. The U.S. Army Natick Research, Development, and Engineering Center (NRDEC) recently decided to re-evaluate their certification of these provisions based on calculations which suggested the provisions did not meet the specified requirements of MIL-STD-209G, October, 1986, Slinging and Tiedown Provisions for Lifting and Tying Down Military Equipment. The U.S. Army Materials Technology Laboratory (MTL), Watertown, MA, was asked by NRDEC to examine these provisons under various loading conditions. Static and fatigue tests were conducted on provisions which had been strain gaged to monitor their load-strain response. Metallographic and nondestructive examinations were performed to detect damage in the strained provisions. An elastic-plastic finite element analysis was used to estimate the material properties and design parameters required to adhere to the specified requirements. Out-of-plane strains were measured during an actual lift of a vehicle.

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PREFACE

This work was done at the request of the U.S. Army Natick Research, Development, and Engineering Center (NRDEC), Natick, MA, and involved the coordinated efforts of three technical branches at the U.S. Army Materials Technology Laboratory (MTL): the Metals Research Branch, the Mechanics and Structures Branch, and the Materials Testing and Evaluation Branch.

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INTRODUCTION

The High Mobility Multipurpose Wheeled Vehicle (HMMWV) is equipped with two front lifting provisions. The provisions consist of inverted U-shaped bars or "hooks" which are welded to a mounting bracket, supporting the vehicle during external airlift operations. Safety considerations demand that these hooks meet strict requirements to preclude in-service failures. MIL-STD-209G[1] addresses the design criteria for provisions of this type, and NRDEC is responsible for certifying Army and Marine Corps airlift systems.

Calculations performed by the Naval Civil Engineering Laboratory (NCEL) had suggested that the design of the HMMWV provisions did not conform to MIL-STD-209G. Specifically, MIL-STD-209G states that "no permanent deformation or set in the provision or other equipment structural components shall result from the application of (the design) loads to the provisions." However, the finite element analyses by NCEL showed that permanent deformation would be expected in the bar portion of the provision. Based on these results, the U.S. Marine Corps (USMC) restricted external lifting of HMMWVs to emergency missions only. This caused NRDEC to re-evaluate the HMMWV front lifting provisions.

As part of this evaluation, NRDEC requested MTL to perform a variety of tests as outlined in a letter to MTL dated 22 July, 1988, and in MTL's responses to NRDEC dated 8 August, 1988 and 9 September, 1988. MTL's tests were designed to:

1. Determine the extent (or existence) of plastic strain (permanent deformation) experienced by the provisions due to the design loads.

2. Subject a provision to extended cyclic fatigue loads to simulate in-service loadings while monitoring the provision's strain response.

3. Examine several provisions which experienced static, fatigue, or in-service loadings using nondestructive and standard metallographic techniques to discover any early signs of damage.

4. Perform an elastic-plastic finite element analysis to compare with NCEL results and the actual tension tests for the provisions. The finite element model estimates the design parameters required to prevent permanent deformation.

5. Advise NRDEC on the performance of the HMMWV provisions during the testing performed at MTL.

6. Make recommendations to NRDEC concerning possible changes to MIL-STD-209G.

7. Determine the magnitude of the effects of out-of-plane stresses on the strains in the provisions. This was accomplished through a lift test of an actual HMMWV using standard rigging.

1. MIL-STD-209G. *Slinging and Tiedown Provisions for Lifting and Tying Down Military Equipment.* October 1986.

EXPERIMENTAL PROCEDURE

Mechanical Testing

Three HMMWV front lift provisions were provided for static testing. All three provisions were sandblasted to expose bare metal. One provision was coated with brittle lacquer (Stresscoat) to verify the regions of increased stress, and the other two specimens were strain gaged in locations specified by NRDEC and shown in Figure 1. The strain gages used throughout were 1/4-inch, 350-ohm gages mounted with an epoxy adhesive (EPY 150). Data was monitored via the OPTILOG (TM) data acquisition system for the static tests.

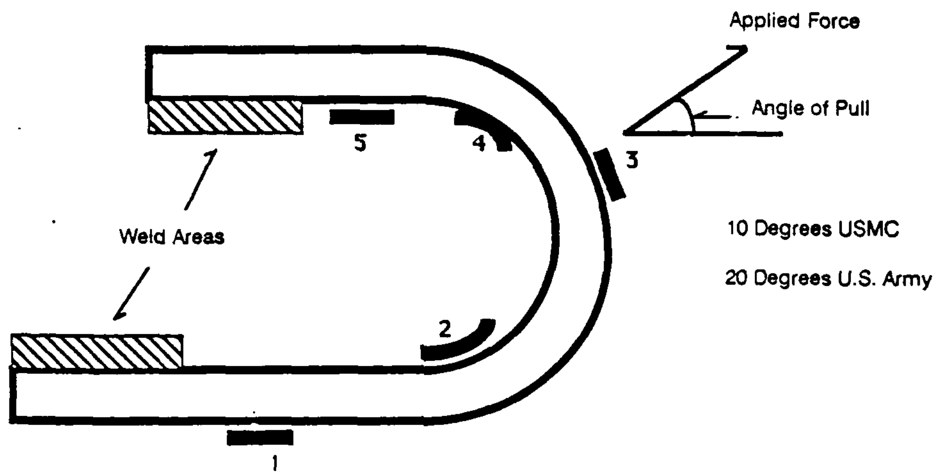


Figure 1. HMMWV provision schematic showing strain gage locations (not to scale).

Tension tests were conducted on an Instron 50,000-lb electromechanical machine using a mounting fixture provided by NRDEC. This fixture allowed the force to be applied at two different angles. The fixture can be seen in Figure 2. A 10-degree angle represented the lifting configuration used by the U.S. Marine Corps, and a 20-degree angle was used to simulate the U.S. Army airlift configuration. The first static test was performed on the specimen with the brittle lacquer coating using the 20-degree angle of pull. The specimen was loaded to 8000 lb, but no evidence of lacquer cracking was detected, nor was any permanent deformation visibly noticeable. The relative humidity in the laboratory and application procedure for the coating may have inhibited lacquer cracking. The second and third tests were conducted using the two strain-gaged provisions. During each test, each provision was stressed three times to the following prescribed loads. Test 2 (10-degree pulling angle) loaded the provision to 8000 lb, while Test 3 (20-degree pulling angle) loaded the provision to 8650 lb. Autographic records of load versus strain were obtained for each strain gage to measure any concurrent and residual deformation.

A fatigue test was conducted on the provision which had been coated with brittle lacquer after it had been cleaned and strain gaged at three locations (positions 1, 3, and 5 in Figure 1). The MEGADAC (TM) high speed data acquisition system was used to obtain the load-strain data. The load spectrum for the test was established by NRDEC. The loads were chosen to simulate both normal and severe loading conditions encountered during external air transportation by helicopter. Tension-tension cyclic test were performed on a MTS 150,000-lb servo-hydraulic machine, using the same mounting fixture as used for the static tests, and a loading angle of 20 degrees. The testing configuration is shown in Figure 2.

The load waveform provided by NRDEC was a combination of four simple loading functions, designated F1 through F4. The form of these functions is given in Figure 3, and the constants associated with each individual function are given in Table 1. The applied load is expressed in Gs, which is the total load applied to the provision divided by the load caused by only the static vehicle weight (1G=2703 lb). The four simple functions each represent a single loading cycle. The distribution of these loading cycles per 1000 total cycles was as follows: F1-495 cycles (1.75G spike), F2-495 cycles (1.75G ramp), F3-9 cycles (2.5G), and F4-1 cycle (3.2G). A total of 18,810 cycles were performed.

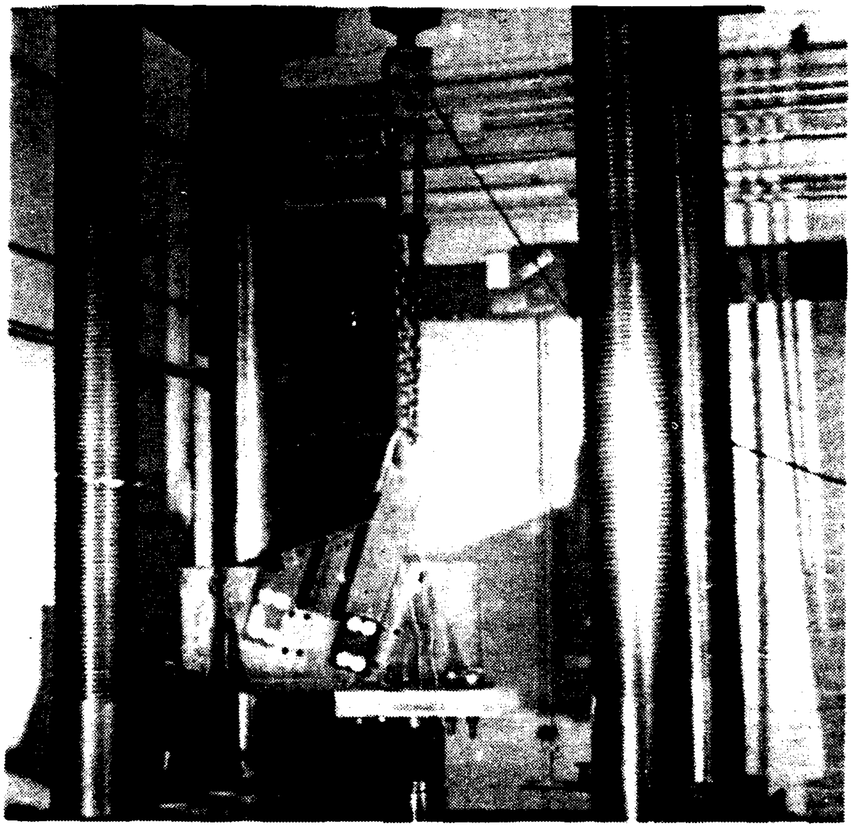


Figure 2. Loading configuration used for fatigue testing. Mounting apparatus was used for static and fatigue tests.

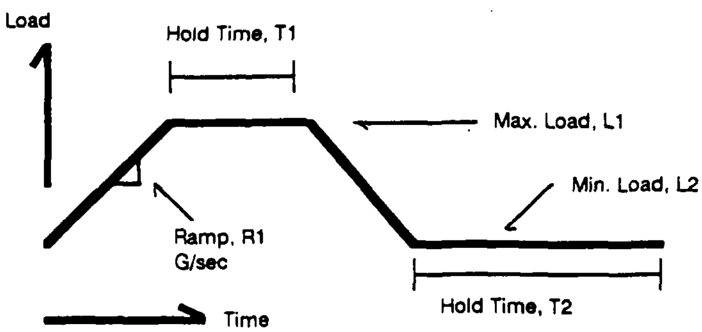


Figure 3. Schematic of loading functions used during fatigue test.

Table 1. LOADING PARAMETERS FOR FATIGUE TEST

Function	Ramp (G/sec) R1	Max. Load (Gs) L1	Holds (sec) T1	T2	Min. Load (Gs) L2
F1	9	1.75	0.08	15	1.0
F2	0.1	1.75	15	15	1.0
F3	0.1	2.5	15	15	1.0
F4	0.1	3.2	15	15	1.0

Upon the completion of this test, a more severe cyclic test using only F4 (the 3.2G function) was performed. An additional 5332 cycles between 3.2G and 1G were completed before the test was stopped for nondestructive and metallurgical examinations.

Tension tests were conducted using material taken from the straight portions of the U-shaped bars of two other USMC HMMWV provisions. These six cylindrical samples had nominal diameters of 0.114 inch and gage lengths of 0.45 inch. Strain gages were applied to the specimens to obtain autographic load versus strain data. A crosshead speed of 0.005 inch/minute was used on all six specimens.

A simulated HMMWV airlift test was conducted to give more detailed knowledge of the airlift procedure. It also provided a means by which the in-plane (in-plane as defined by the plane of the U-shaped bar) loading assumption used in the finite element models and the other mechanical testing would be verified. The magnitude of out-of-plane provision loads and strains could be determined by this test.

The simulated airlift was performed by lifting a HMMWV with an overhead crane. Provisions on this particular vehicle were never loaded before this test. Air transport slings with in-line load cells using the Army (20-degree) load angle were provided by NRDEC. A total of 11 strain gages were located on each provision to measure both in-plane and out-of-plane strains. Strain and load data were obtained with the MEGADAC dynamic data acquisition system. A remote triggering device was used to activate the MEGADAC system prior to each lift. The gross vehicle weight for the test was 7690 lb, which was obtained by adding a 2540-lb weight to the initial vehicle weight of 5420 lb. The weight was carefully positioned to ensure a baseline load of 2703 lb for each front provision. This load matches the baseline load of 1G used in the fatigue test.

Nondestructive Examinations (NDE)

Three NDE tests were performed on the fatigued specimen and the three fielded USMC HMMWV provisions. Radiography was used to examine the weld areas for possible flaws. A fluorescent dye penetrant examination and magnetic particle inspection of the provisions were performed to detect surface cracks. The dye penetrant is applied to the provision, and the surface is subsequently cleaned. Any dye that has penetrated into surface cracks will seep back out of the flaw and can be visually detected. The magnetic particle tests introduce a strong magnetic field into the specimen, and iron filings are then applied. Surface flaws alter the adjacent magnetic field, and the filings make this change apparent.

Metallography

Samples for metallographic examination were mounted and polished mechanically through a 0.05 micron alumina slurry. Edges of the sectioned provisions were examined for possible flaws and surface cracks. Edge retention was enhanced by the addition of alumina spheres to the mounting material. Microstructural characterization was performed after using a 3-percent Nital etch.

A sample for examination by scanning electron microscopy (SEM) was sectioned from the provision that was fatigue loaded. The selected area had shown evidence of a small flaw in the NDE dye penetrant tests. Sputtering was not employed. After viewing with the electron microscope, the sample was sectioned transversely through the flaw for metallographic examination.

Finite Element Analyses

Structural integrity of the HMMWV airlift provision was also assessed analytically through the use of finite element (FE) models. Initially, a two-dimensional (2-D) linear elastic FE model was created to verify previous analyses by NRDEC and NCEL. This verified that stresses were applied that significantly exceeded the material's yield strength. Consequently, plastic deformation was expected to occur, and thus, an elastic-plastic FE model would be required to describe the yielding of the HMMWV provision.

MTL's FE modeling was conducted using the ABAQUS software package. Out-of-plane components of the provision's load are considered negligible, so a 2-D model was used. Elastic-plastic material behavior was assumed. The model represented the U-shaped portion of the lift provision above the fillet welds, and consisted of 35 2-noded beam elements. Fixed boundary conditions were applied at both ends to simulate the presence of the welds. The model was loaded by applying a concentrated point force at the chain/hook interface. This force was applied nonconservatively, which allowed the force vector to rotate with the same rotation as the loaded node. The three load cases considered are listed in Table 2.

Table 2. LOAD CASES FOR THE FINITE ELEMENT MODEL

	Load (lb)	Angle (deg)*
Case #1	9300	20
Case #2	8650	20
Case #3	9300	5

*Angles were taken with respect to the provision's local vertical axis

The material parameters used in the FE model were derived experimentally from actual HMMWV provision material. The average value of 87.5 ksi (Table 3) for the 0.2-percent offset tensile yield strength was used in the FE model, along with the true stress-true strain curve of Figure 4. Strains greater than three percent were extrapolated using the power hardening law.

Linear-elastic models for different bar ("hook") diameters were created to determine the minimum bar diameter required to prevent significant yielding. Increasing the hook's diameter while holding the dimension between the hook's inner surfaces constant changes the hook centerline. A FORTRAN program was created to compute new nodal coordinates for diameters of 3/4, 7/8, 15/16, and 1 inch.

Table 3. TENSILE DATA OF PROVISION MATERIAL
(Material for tensile samples was removed from two USMC HMMWV provisions.)

Specimen No.	0.2% Yield Strength (ksi)	Ultimate Tensile Strength (ksi)
1	87 5	88.2
2	88.8	89.2
3	87.4	88.3
4	79.6	84.5
5	87.1	89.1
6	88.7	90.2

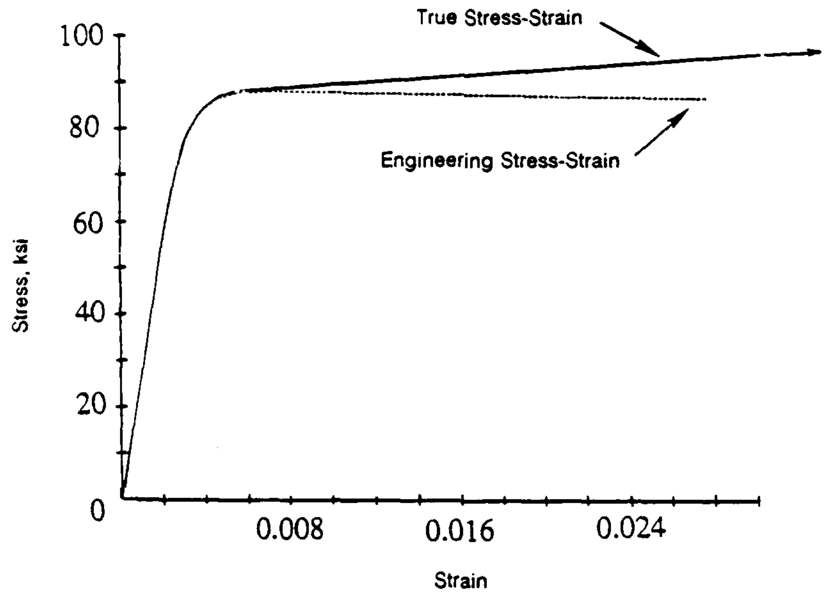


Figure 4. Typical tensile behavior of provision material.

RESULTS AND DISCUSSION

Material Characterization

The microstructure of the HMMWV provision material is shown in Figure 5. This sample was sectioned parallel to the axial direction. Significant banding can be seen in the micrographs, and the level of cold work in the material is estimated to be less than 50 percent.[2] The dark regions of the microstructure are fine pearlite, and the amount is typical of a slow-cooled 1020 steel.[3]

The typical tensile stress-strain response of the provision material is given in Figure 4. Six tensile samples were tested, and the results are tabulated in Table 3. The average value of the yield strength (0.2-percent offset) is 87.5 ksi. Hardness measurements were also taken from different areas of the USMC provisions. The average value taken along the center (neutral) axis of the provision was HRB 90. Readings taken near the edges of the bar in the

2. ASM Metals Handbook. v. 9, 9th Ed., 1985, p. 180-181.
3. ASM Metals Handbook. v. 9, 9th Ed., 1985, p. 186.

curved region (but away from the neutral axis) averaged HRB 93, while values taken near the weld areas averaged HRB 85. Five hardness measurements were averaged for each case.

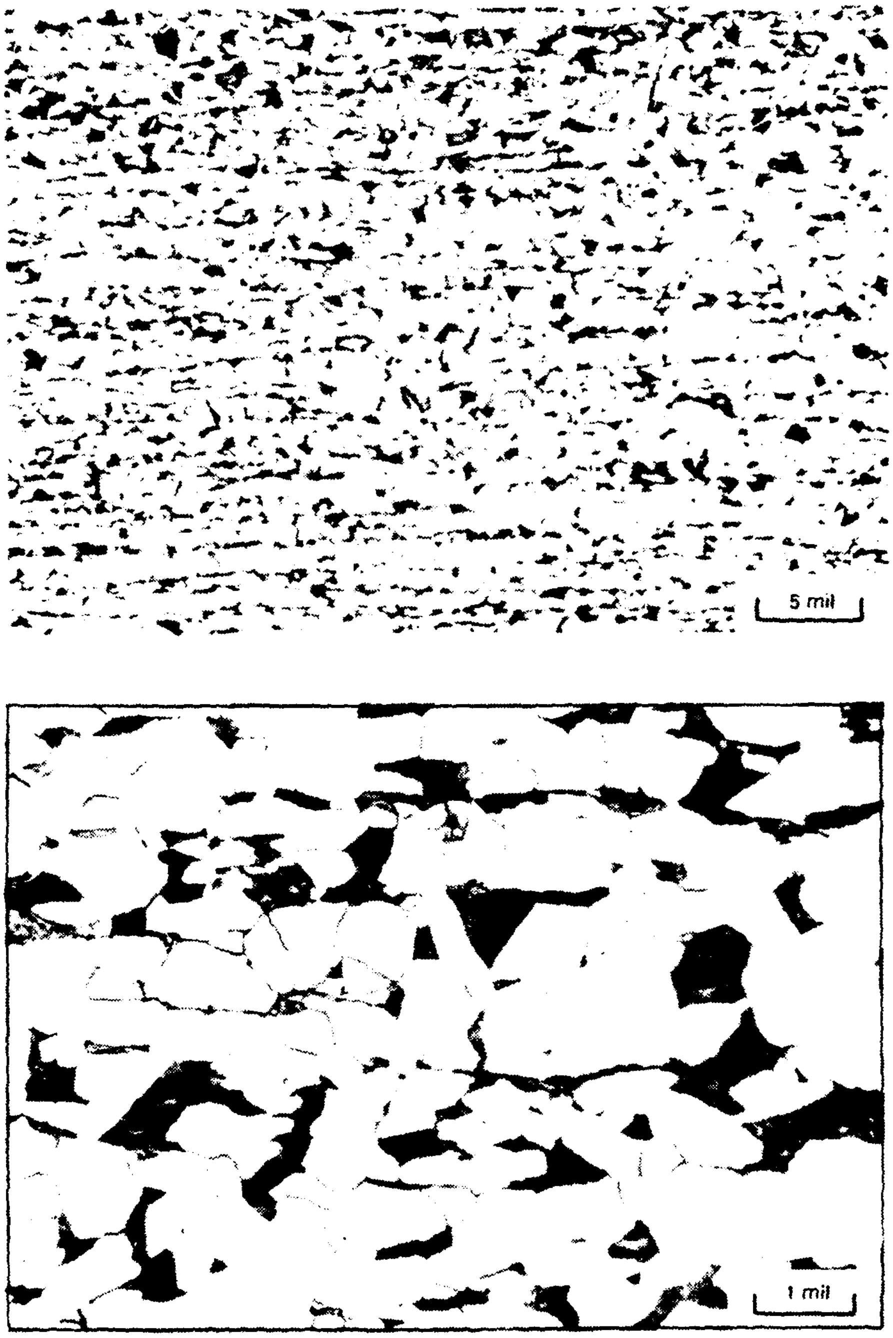


Figure 5. Microstructure of provision material, Nital etch. Banding can be seen in microstructure. Dark regions are pearlite.

Static Tests Results

Figure 6 shows the load-strain data for three of the strain gages for the first pull of the provision tested at 8650 lb/20 degrees. Upon unloading, it is obvious that permanent strain has resulted. The largest plastic strain measured, 2.9 percent, was found at gage number 1 (Figure 1), and all of the gages showed some signs of plastic flow. Gage number 3, directly above the loading point, experienced approximately 1-percent strain before the gage debonded. This provision was visibly deformed.

The provision loaded to 8,000 lb at 10 degrees also showed plasticity from the strain-gage measurements. The largest measured strain was 1.09 percent at gage number 2. Again, all five gages measured some permanent deformation, and gage number 3 debonded. Visual inspection of this provision to detect permanent set was inconclusive.

The second and third pulls on these provisions causes only small increases in the total (accumulated) plastic strain because of work hardening. For example, the plastic strain at gage number 2 of the 8,000-lb/10-degree specimen increased from 1.09 percent to 1.27 percent after the third pull. This small increase in accumulated strain was not visually noticeable. Hysteresis was seen in the load-strain data. Figure 7 shows the load-strain response for gage number 2 in the 8000-lb/10-degree test for all three loadings.

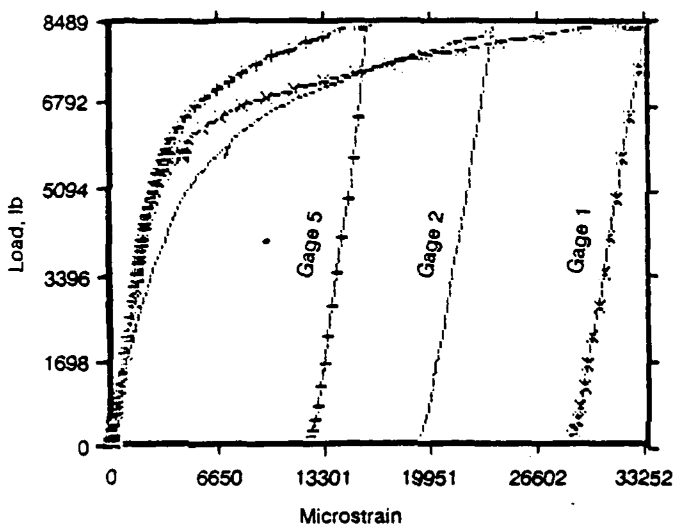


Figure 6. Load versus strain data for the initial loading of a provision to 8650 lb at 20 degrees. Gages correspond to Figure 1.

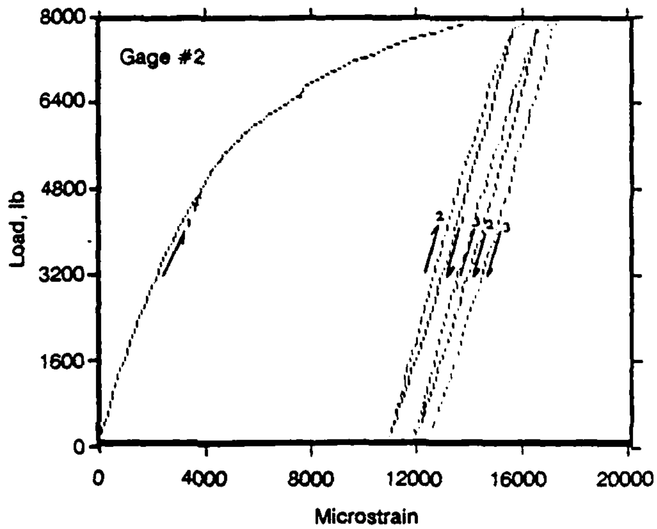


Figure 7. Load versus strain data for gage number 2 for loadings 1, 2, and 3. Provision was loaded to 8000 lb at 10 degrees.

These statically-tested provisions were sectioned near each strain gage for metallographic analysis to detect flaws introduced by the static tests. Figure 8 shows a section at the outer surface. No unusual flaws or cracks were detected in either provision.

These static tests demonstrated that strain gages have detected permanent deformation in the provisions under both Army and USMC loading conditions. The 8650-lb/20-degree loading condition produced a visible permanent set, and therefore, clearly did not meet the requirements of MIL-STD-209G. However, MIL-STD-209G does not set forth guidelines regarding how permanent deformation should be detected. According to NRDEC, visual detection is the most common method. The provision tested with the 8000-lb/10-degree condition did not clearly fail the test outlined in MIL-STD-209G, unless the strain-gage measurements are used.

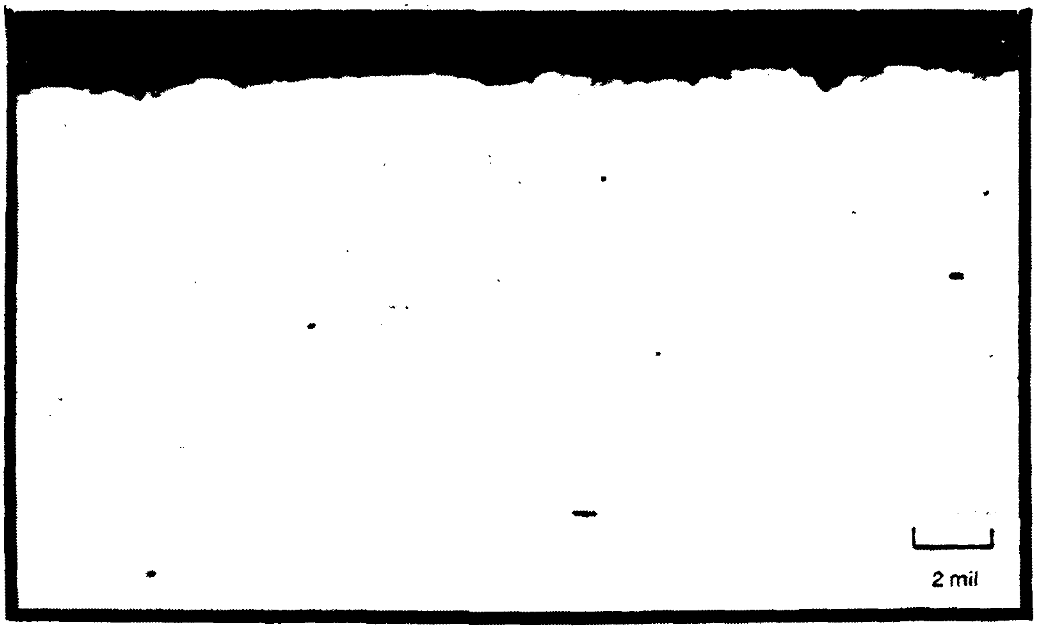


Figure 8. Section of provision tested statically to 8650 lb at 20 degrees. No unusual flaws or cracks are seen. Unetched.

Also, it should be pointed out that if the manufacturer were to proof-test all of the provisions by pulling them to 8650 lb before delivery, the *additional* deformation would not be visually noticeable. Work hardening of the provisions causes the additional plastic strain on subsequent pulls to be greatly reduced. Therefore, a provision that has been tested once (and thus predeformed) will probably pass the "no deformation" criteria of MIL-STD-209G on a second test if a visual technique is employed.

MIL-STD-209G states "no permanent deformation," but this is not a clearly defined concept. Does this mean the material should not deviate at all from linear elastic behavior? If so, how much deviation constitutes failure? How is the deviation measured? In a letter to NRDEC from the Military Traffic Management Command (MTMC), Transportation Engineering Agency (the proponents of MIL-STD-209G) dated 23 September, 1988, an interpretation is given, stating "a predetermined, allowable offset value...is not allowed when using the design load," and, "the success or failure of MIL-STD-209G tests may be determined by visual inspection or by using strain gages." Plastic strains greater than 1 percent were measured for the 8000-lb/10-degree configuration, but the visual inspection was inconclusive. This guidance is clearly contradictory. This also raises serious doubts about provisions for other vehicles or systems which passed visual tests for "no deformation," if MTMC declares that 0.2-percent plastic deformation is not allowable.

A failure criterion must be defined if the Army is to expect compliance with MIL-STD-209G. Failure could be defined simply by one of the following three methods: (1) exceeding some specified amount of allowable plastic deformation (as measured by strain gages), (2) exceeding some allowable percent deviation in slope from the elastic portion of the load-strain curve (as measured by location specified strain gages), or (3) exceeding permanent displacements that are unnoticeable to an unbiased observer. If one or more of these criteria was chosen, each, in turn, would need further definition. Simply stating "no deformation" in an area of technology where strain gages and techniques allow for detection of extremely small values of plastic strain is not practical. There is evidence to suggest that materials under any load undergo some plastic deformation (although it may be extraordinarily small). Therefore, new failure criteria must be clearly written to assure uniform interpretation. In its current form, MIL-STD-209G lacks this clarity, and its interpretation by MTMC compounds the issue.

Fatigue Test Results

The load-strain behavior of the provision during the fatigue test is typified by Figure 9. In this figure, the strain-gage response for the fourth 3.2G cycle (the 2422nd total cycle) is given. Because of possible gage debonding, the accuracy of data from gage number 3 is in question. Hysteresis in the plastic strains measured indicate that low cycle fatigue processes may be operable when the provision is cycled to the 3.2G load.[4,5] Data for the 2.5G level are similar, but indicate even smaller levels of reversed plasticity. No hysteresis is apparent for load cycles that only reach the 1.75G loads, whether pulsed or ramped loadings were used. This provision withstood 18,810 total cycles of the NRDEC prescribed loadings.

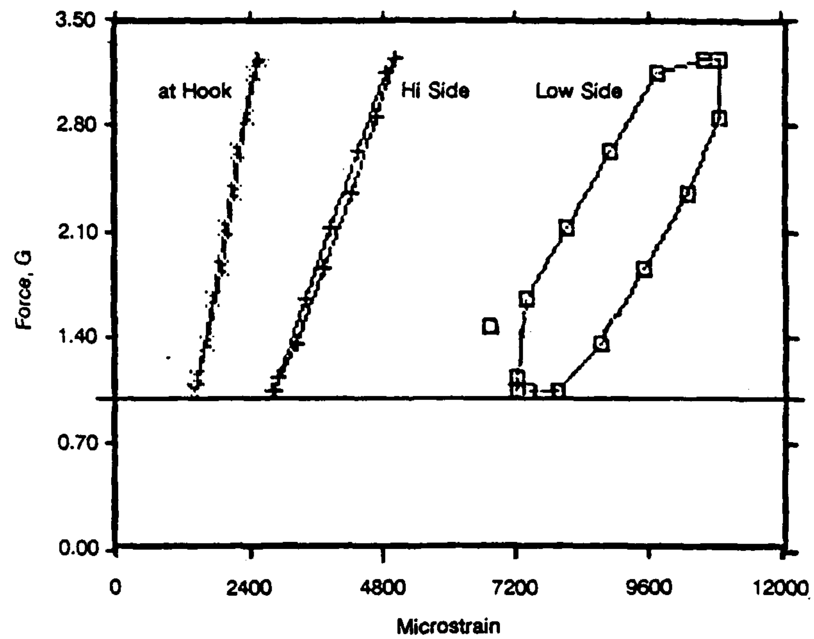
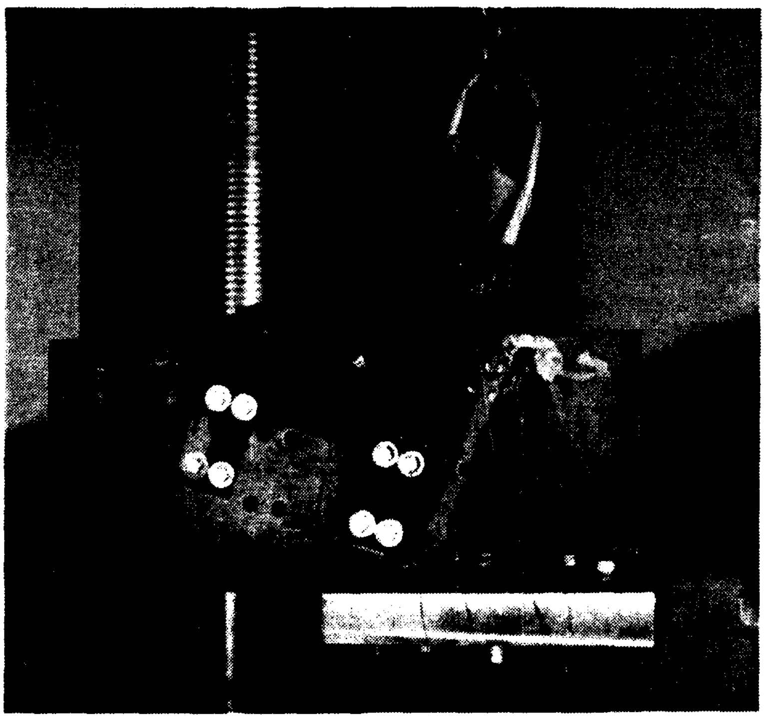


Figure 9. Typical load versus strain data taken during the first long term fatigue test. Data shown are for the 3.2G load cycle, total cycle number 2,422. Hystersis is seen in the data for gage number 1. Low side is gage 1, at hook is gage 3, and high side is gage 5 (Figure 1).

Because only the 3.2G loads were producing significant hysteresis, the second, more severe, test used only the 3.2G loads. An additional 5,332 cyles of the 3.2G load were applied, and the provision continued to function properly. At this point, the test was stopped to allow for NDE and metallographic examinations. The provision at the conclusion of the fatigue test is shown in Figure 10. A small crack was visually detected in one of the spot welds that holds on the top cover plate. The location of this crack is shown in Figure 10a.

4. COFFIN, L. F. *A Study on the Effects of Cyclic Thermal Stresses on a Ductile Metal.* Trans. AIME, no. 76, 1954, p. 931.
5. MANSON, S. S. *Behavior of Materials Under Conditions of Thermal Stress.* NACA technical note 2933, 1954.

(a) Deformed provision and location of cracked spot weld



(b) Mounting apparatus and provision

Figure 10. HMMWV provision at fatigue test conclusion.

The spot welds are used to hold the cover plate in position, but the cover plate is not a major load-bearing component. Therefore, this crack, confined to the spot weld, was considered to be unimportant.

The fatigued provision was examined using radiography and the dye penetrant NDE techniques. The dye penetrant indicated the presence of a surface crack within an indentation caused by the loading chain. No other surface flaws could be detected on the bar. Radiography was used to examine the weld area. A weld on one side of the provision had undergone two welding passes. Though lack of complete weld penetration was observed, the weld showed no signs of fatigue failure. A schematic of the weld area as revealed by the radiographs is shown in Figure 11.

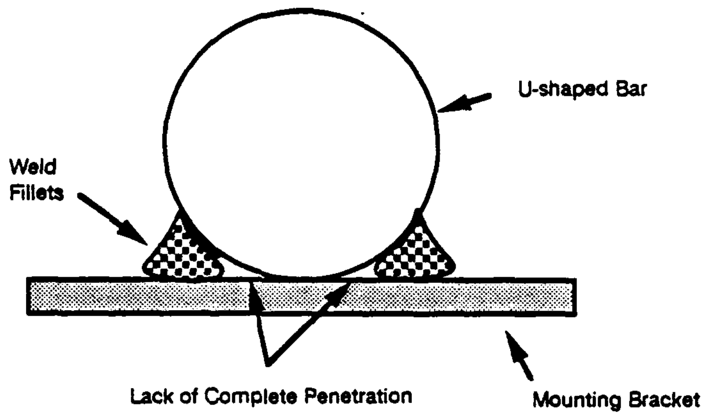
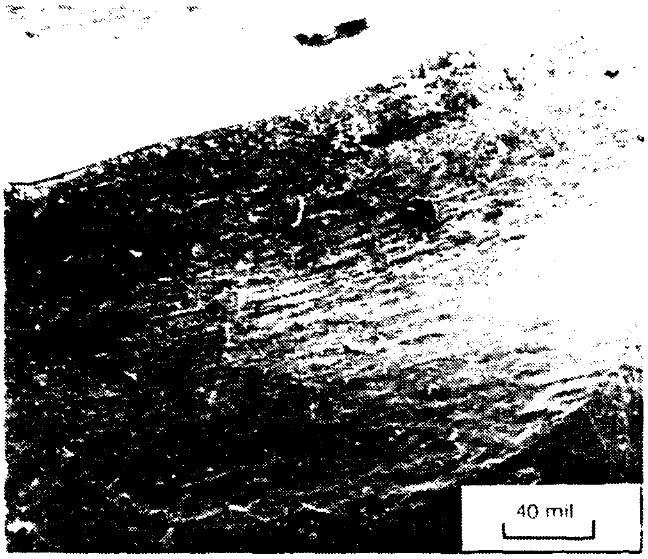


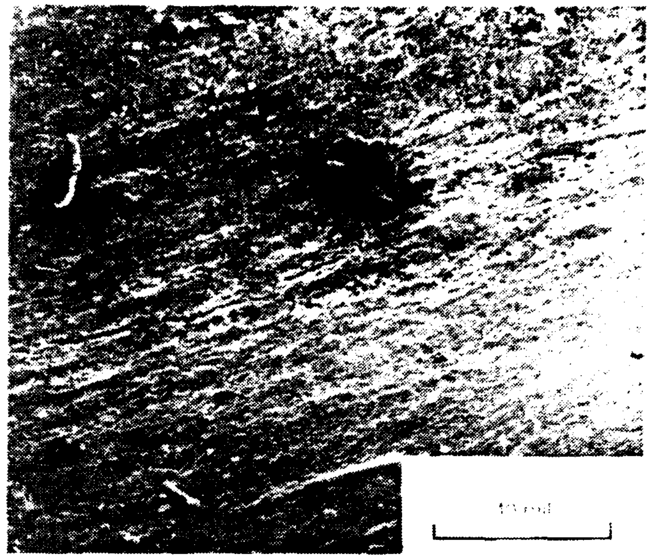
Figure 11. Schematic of welds as revealed by radiography.

After the nondestructive examination of the fatigue test sample was complete, the region with the indentations and flaw was sectioned and examined by scanning electron microscopy. A crack was observed in the location specified by the dye penetrant test, and is shown in Figure 12 (a-c). The crack has a surface length of about 120 mils, but the depth of the crack cannot be determined from SEM photos. This sample was sectioned transverse to the crack near the center of its surface length. This sectioned view is seen in the optical micrographs of Figure 13. The depth of the crack at this point is about 40 mils, giving the crack front a semicircular shape. Further examination of the crack tip after etching the sample revealed a blunt crack tip. This demonstrates that the full crack depth was accurately measured from Figure 13. It was not determined when the crack was initiated during the fatigue test. Whether this was a critical crack that would have resulted in the eventual failure of the provision under continued cycling is also unresolved.

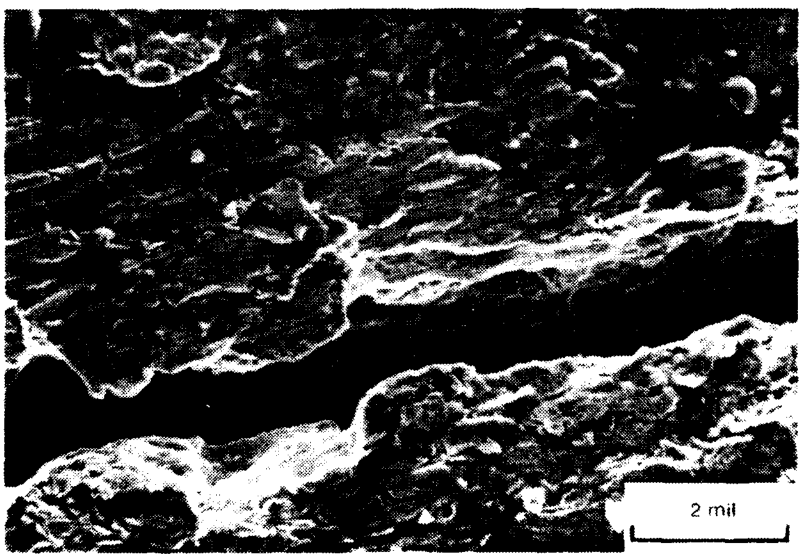
The formation of this crack within the indentation was somewhat unexpected, as the *underside of the provision* is nominally under compressive/compressive cyclic bending stresses. Possible mechanisms of formation include: (1) the interaction of residual tensile stresses from the indentation with the nominal bending stresses, causing tension/tension fatigue crack nucleation and propagation; (2) the formation of the crack upon initially indenting the material, with fatigue crack growth into the residually stressed region; and (3) the initiation and growth of the crack by contact fatigue. Other mechanisms may also be possible. Knowledge of how and when the crack formed is vital to assess its severity; both of these questions remain unanswered. It would require further experimental studies to separate out the possible mechanisms.



(a) Indentation on underside of bar where load is applied (crack is not visible)



(b) Crack is just below foreign matter



(c) Crack at higher magnification

Figure 12. Crack found in chain indentation as viewed by SEM.

Figure 13. Crack in chain indentation sectioned transversely. Crack depth is approximately 0.040 in.

The fatigue test demonstrated that the provision can withstand significant plasticity and continue to perform satisfactorily for extended periods of severe loadings. The two cracks that developed should not overshadow the successful performance of the provision during the fatigue test. According to NRDEC, the loads that were applied to the provision represented several complete vehicle lifetimes (in the first 18,810 cycles), and the 5,332 cycles to 3.2G exaggerate in-service conditions even further. Despite these extreme conditions, the provision still accomplished its job throughout the test, and this is supportive of its structural integrity.

Examination of Fielded USMC Provisions

Three fielded provisions were provided by the USMC through NRDEC to look for possible signs of in-service fatigue. These three provisions were examined using radiography, dye penetrant, and magnetic particle inspection. No surface flaws were detected using either dye penetrant or magnetic particle inspection. Radiographs of the welds showed a lace of complete penetration of the weld across the underside of the bar, as was also observed in the fatigued provision (Figure 11). This would be expected using the current design. However, this has not caused any problems in any of the fielded provisions, or in any of the test provisions, so the welds appear adequate. Since no cracks were uncovered using the NDE techniques, two of these three provisions were used to make tensile specimens for mechanical property characterization.

Finite Element Modeling

Plasticity was evident for each loading case given in Table 2. Case number 1 produced the most plasticity, while case number 3 produced the least. After loading the model to the loads specified in Table 2, the model was unloaded to zero load to give permanent displacements and plastic strains. The amount of permanent displacement predicted by the FE model was compared to actual deformation by superimposing the zero load displacement fields of the case number 2 model against the actual deformation of the fatigue specimen as measured by projecting a photo of the deformed specimen. The case number 2 model and the fatigue specimen were both loaded to 8650 lb/20 degrees. Figure 14 shows the superimposed displacements of the FE model and the actual provision. Near-perfect correlation of the displacements is observed. The good agreement is directly related to the use of accurate material parameters, which were derived experimentally. The handbook value of yield strength for a 1020 cold-drawn steel is 30 percent less than the value observed in the tensile tests. The maximum residual plastic strain predicted by the FE model was approximately 5 percent for the case number 1 loading, near the point of concentrated loading.

The FE model can also be used to specify the minimum bar (hook) diameter necessary to prevent plastic deformation. Linear-elastic analyses were performed for five different hook diameters. These analyses produce a maximum stress versus hook diameter curve (Figure 15) which can be used to determine the yield strength-diameter combinations required to avoid plastic deformation. Using the current material's yield strength of 87.5 ksi, a hook diameter of 0.925 inch would preclude yielding beyond 0.2-percent strain for the most severe case, case number 1. The present hook diameter is 0.625 inch.

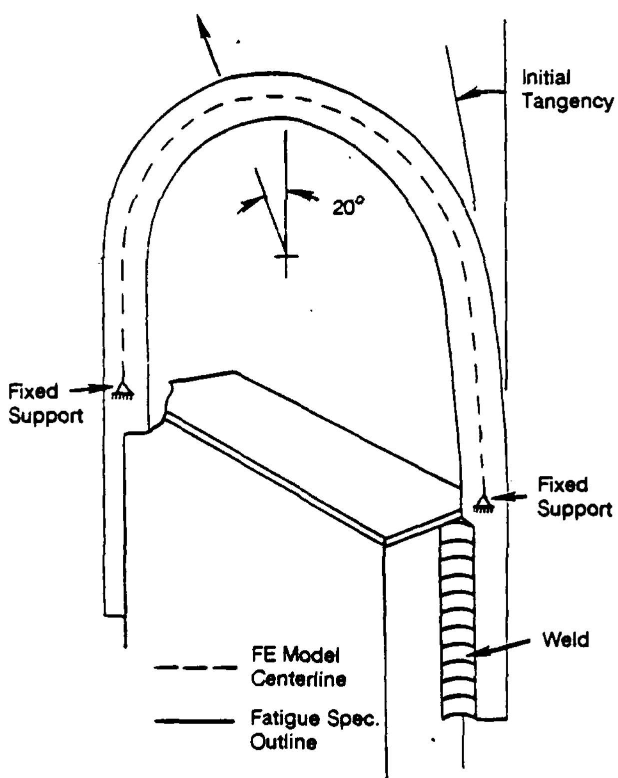


Figure 14. Permanent set comparison between FE analysis and the fatigue specimen.

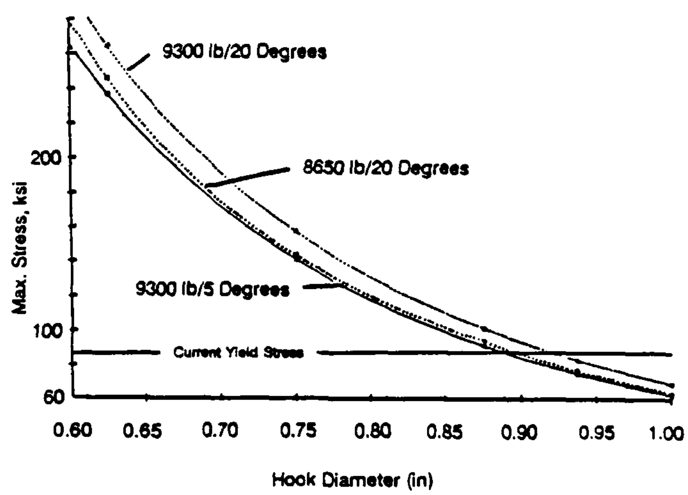


Figure 15. Linear-elastic FE analyses giving maximum stress versus hook diameter for the three different load cases. The provision's yield strength is given by the horizontal line, which shows that a 0.925-inch diameter would be required to prevent significant yielding. The current bar diameter is 0.625 inch.

Simulated Airlift Test

Testing of the provisions was performed by triggering the data acquisition system and then lifting the vehicle. The HMMVW was lifted completely off of the ground in 2 seconds, suspended for 8 seconds, and lowered back to the ground in 2 seconds. A load-time response curve for the left provision is seen in Figure 16. Peak loads for the right and left provisions were 3668 lb and 3251 lb, respectively. No plastic deformation was observed in either of the provisions at these load levels. Peak in-plane strains occurred at the expected locations. Maximum elastic strain values were 0.36 percent and 0.28 percent for the right and left provisions, respectively. The out-of-plane loading angle for the Army configuration is 5 degrees, as shown in Figure 17. This produced a maximum out-of-plane strain on the right provision of just 0.04 percent, which occurred just above the lower weld.

The in-plane loading assumption used throughout all of the testing and modeling was verified for the Army loading configuration. Out-of-plane forces were only 8.7 percent of the total loads. Comparisons of in-plane strains for the simulated airlift test with the finite element analysis demonstrated excellent agreement.

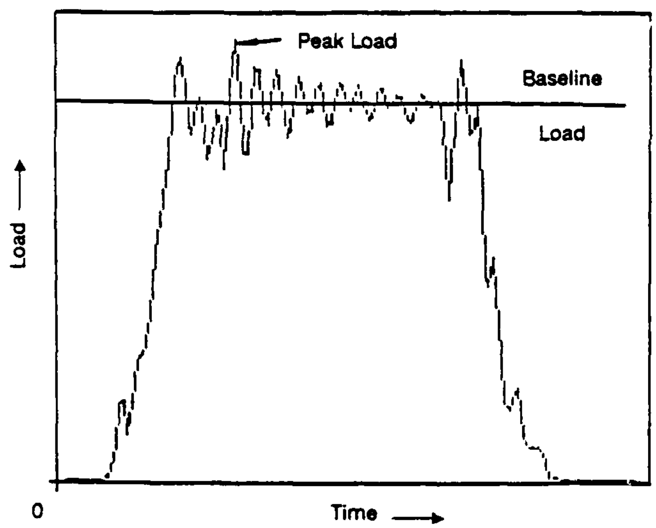


Figure 16. Load-time response curve for simulated air lift test.

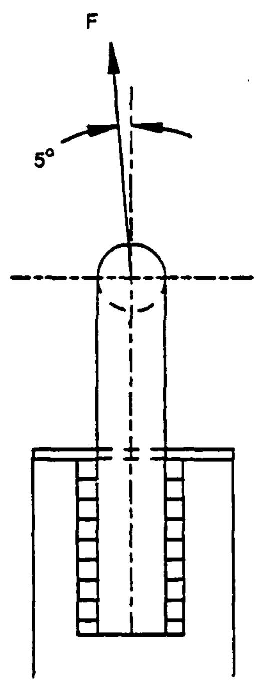


Figure 17. Out-of-plane loading.

SUMMARY

1. Based on strain-gage measurements, significant plastic deformation was observed on all of the HMMWV front lift provisions tested. Visual permanent deformation was also observed for the 8650-lb/20-degree configuration. These results show the provisions do not meet MIL-STD-209G as it is currently written.

2. The lift provision withstood the fatigue test loads prescribed by NRDEC. After 24,142 cycles of two different types of fatigue testing, the provision was still performing satisfactorily. According to NRDEC, the first 18,810 cycles simulated several vehicle lifetimes of airlift usage. The last 5,332 cycles were performed at the severe design load, and this further exaggerates in-service fatigue loadings. **The provision's survival of this extremely severe fatigue test is supportive of its structural integrity.**

3. Two cracks were discovered in the provision after the fatigue test was completed: (1) a crack formed in an indentation caused by one of the chains used for loading the provision, and (2) a spot weld at the corner of the top cover plate fractured. The evolution of the small indent crack is not fully understood, nor is its significance resolved, and NRDEC may want to consider a separate study of the chain indent phenomenon. The spot weld crack on the cover plate allowed for some redistribution of stress. However, this spot weld is not a critical load-bearing component; therefore, this flaw is considered to be unimportant.

4. None of the provisions which had been fielded and airlifted showed any signs of fatigue damage or permanent deformation. Thus, the design loads seem to be well in excess of actual in-service loads.

5. The finite element study showed excellent agreement with the actual deformation of the provision. To prevent significant yielding, a bar of 0.925-inch diameter with a yield strength of 87.5 ksi (the material currently used for the provisions) would be required. The differences between this analysis and the study by NCEL arose from the use of different material properties and the addition of plasticity to the finite element model. The properties used in the current study were measured on actual provision material, and are, therefore, more reliable than handbook values.

6. Out-of-plane strains were determined by the simulated airlift to be very small. Therefore, the assumption of using only in-plane stresses for testing and modeling is verified.

7. MIL-STD-209G needs significant clarification. Currently, there is too much room for different interpretations of MIL-STD-209G, and the motivations behind it are unclear. More specificity is required in how the plasticity should be measured, and allowable tolerances, however small, should be given. Clearly outlined motives for the specifications in MIL-STD-209G would allow NRDEC to make knowledgable exceptions to MIL-STD-209G **if conditions warranted it.**

For example: If the vendor prestrained the current HMMWV provisions (similarly to the static testing required), the additional plasticity that would be measured during testing would be small, and would definitely not be visually noticeable. Essentially, the provisions which "fail" MIL-STD-209G on their first test, will pass on a second try because of work hardening.

8. The fielded USMC HMMWV provisions showed no signs of permanent deformation, even though they have been airlifted. Although the fatigue test has demonstrated that the provisions can withstand the plasticity encountered in testing and still perform satisfactorily, an additional safety measure could be provided by routinely visually inspecting the provisions for permanent deformation with a straightedge template. Deformed provisions could then be replaced.

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LIFT PROVISION - 1LT John H. Beatty, Morris Azrin,
Paul V. Cavallaro, John F. Beatty,
Robert E. Pasternak, and John Nunes

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The High Mobility Multipurpose Wheeled Vehicle (HMMWV) is equipped with two front lifting provisions which support the vehicle during external airlift operations. The U.S. Army Natick Research, Development, and Engineering Center (NRDEC) recently decided to re-evaluate their certification of these provisions based on calculations which suggested the provisions did not meet the specified requirements of MIL-STD-209G, October, 1986, Slinging and Tiedown Provisions for Lifting and Tying Down Military Equipment. The U.S. Army Materials Technology Laboratory (MTL), Watertown, MA, was asked by NRDEC to examine these provisons under various loading conditions. Static and fatigue tests were conducted on provisions which had been strain gaged to monitor their load-strain response. Metallographic and nondestructive examinations were performed to detect damage in the strained provisions. An elastic-plastic finite element analysis was used to estimate the material properties and design parameters required to adhere to the specified requirements. Out-of-plane strains were measured during an actual lift of a vehicle.

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