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PERFORMANCE EVALUATION OF A MAGNESIUM ALLOY TRUCK WHEEL

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ABSTRACT

In certain engineering structures weight is of paramount importance. The problem is really two-fold:

1. The excessively stressed areas must be located and remedied to achieve sufficiently long life.
2. The low-stressed areas must be located and lightened to achieve least weight.

This leads to a concept of design efficiency, namely performance per unit weight.

Applying this concept to a magnesium truck wheel, this paper discusses:

1. The advantages of magnesium over steel.
2. The use of Stresscoat and strain gages to locate and measure the strains in the wheel during actual truck maneuvers.
3. The fatigue analysis and performance evaluation.
4. The relative merits of testing-to-failure methods and experimental stress analysis techniques.

SYMBOLS

MII = microinches per inch.
KSI = thousands of pounds per square inch.
R = ratio of minimum to maximum stress.
Mc/I = nominal bending stress.

INTRODUCTION

Weight is of paramount importance in many engineering structures. The locomotive designer utilizes weight to make his machine powerful, hence is little concerned about material which adds pounds but contributes nothing to the usable strength and life of his machine. To an airplane, extra pounds spell the difference between flying and not flying. The airplane industry logically enough was the first to extensively explore the use of light metals and the means of detecting excess metal which did not do its fair share of work. This was done not only to make the plane capable of flying, but in the more refined stages, to replace the excess parasite metal with fare-paying passengers. The problem is not only to locate and remedy the excessively stressed areas to achieve performance, but also to locate and lighten the low-stressed areas to achieve least weight. This leads to a concept of design efficiency, namely performance per unit weight.

In ordinary testing-to-failure methods, the excessively stressed areas are located by failures. Since without further information the resulting remedy usually involves adding weight, the design efficiency is not always improved. With the use of experimental stress analysis, it is possible to evaluate both high and low-stressed areas, and, as has been demonstrated many times, achieve higher performance with less weight which is a real improvement in design efficiency.

The importance of achieving such design efficiency in an airplane is fairly obvious. Other applications are somewhat more difficult to evaluate. For instance, the trucking industry, for many years concerned almost entirely with endurance of its machines, has found that the use of light metals with its weight reduction means better performance, greater load capacity, and more economical

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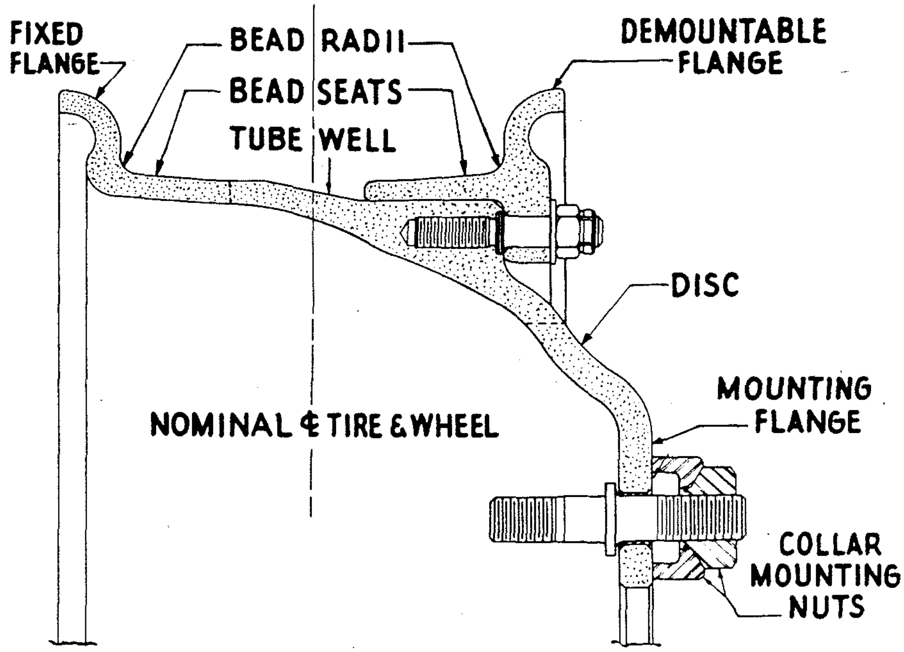

FIGURE 1. CROSS-SECTION OF TEST WHEEL.

operation(1)*. Although this application has been mostly in the truck body and frame, the analysis described in this paper suggests that magnesium wheels may also be used to advantage in much the same way.

In a wheel of the type considered, nearly all loads impose bending on various elements of the structure. Light metals, especially magnesium, achieve one of their greatest advantages in bending. For a given weight a magnesium section can be roughly four times as thick as a steel section. Since the nominal bending stress, Mc/I, on the surface varies inversely as the square of the thickness, then for rectangular beams of magnesium and steel having equal weight, length, width and bending load, the maximum stress on the steel will be 16 times the maximum stress on the magnesium. Likewise the deflection of the steel beam will be roughly 14 times that of the magnesium. The endurance limit** of magnesium in completely reversed bending will range from $\frac{1}{8}$ to $\frac{1}{2}$ that of steel depending on the type of alloy and type of fabrication compared(2). Again using a rectangular beam of cast magnesium with length, width, and bending load equal to that of a high strength steel beam, adjusting the thickness so that each is being stressed to its endurance limit, it can be shown that the magnesium beam weighs roughly half as much as the steel beam and deflects less than half as much.

It was agreed by the parties concerned with this project that a magnesium alloy wheel, which would give sufficient performance with possibly half the weight of a steel wheel of the same size and type, would provide sufficient tactical and economic advantage to justify the cost of a short-time development program. Severe restrictions of cost and time on the program ruled out the possibility of any extensive fatigue testing to failure and left the performance to be evaluated largely by experimental stress analysis. The only provision for actual fatigue testing was for one wheel to be rolled on a laboratory flywheel dynamometer.

On the basis of available information, a design was concocted and test units manu-

* Numbers in parentheses pertain to references at end of paper.

** The endurance limit of magnesium referred to in this paper is technically the fatigue limit at 10^7 cycles. For all practical purposes it can be called endurance limit because the fatigue limit at 10^9 cycles is only slightly lower than at 10^7 cycles.

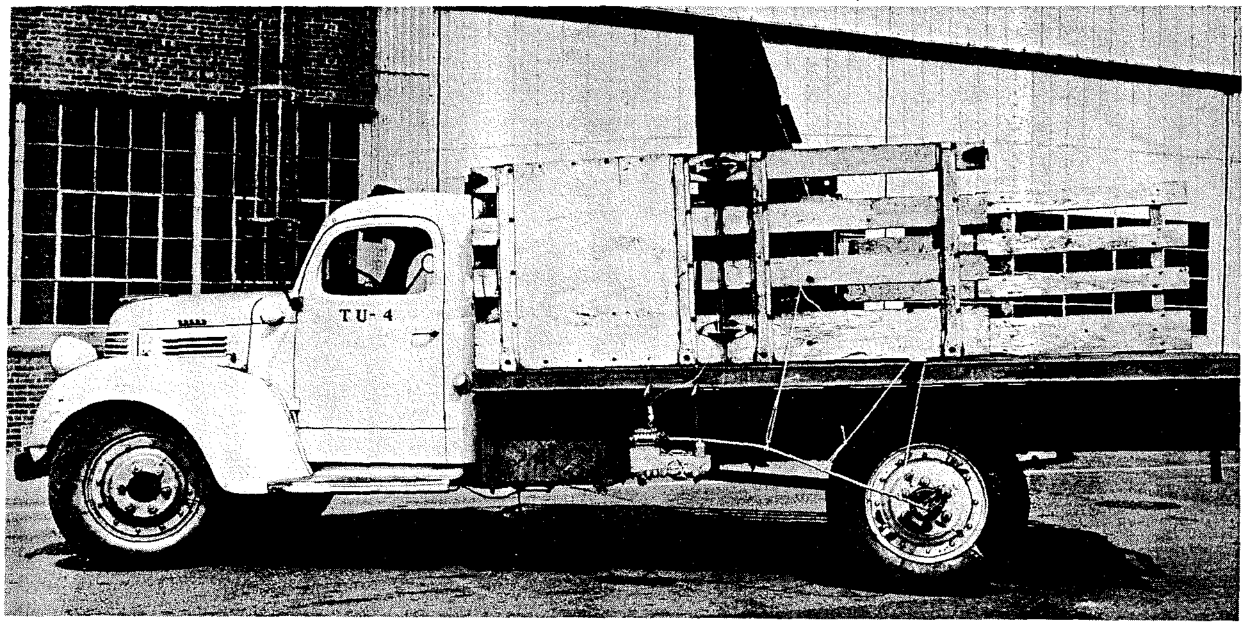

FIGURE 2. TEST TRUCK.

factured. This design provided only a 35% reduction in weight over a steel wheel of the same size and type.

The objectives of the program were:

1. to determine whether the wheel would satisfactorily meet the life requirement;
2. to determine the degree of design balance and efficiency prevailing in the wheel for the required life expectancy;
3. to determine the relative fatigue damage caused by various loads; and
4. to establish a basis for the design of a wheel which would meet both the life and weight requirements.

THE TEST PROGRAM

The test wheel was a 6.00CT-20 size, of a conventional bowl shape, with a bolted-on demountable flange, made of Dowmetal A-T4 and using an 8.25-20 tire. A cross-section of this wheel is shown in Figure 1.

Since information regarding load factors and components was very meager, it was highly inadvisable to resort to laboratory tests with assumed loads. The test wheels were, therefore, installed on a truck, Figure 2, various degrees of loading being achieved by sand bags. Truck maneuvers included straight driving, turning, braking, washboard road, sharp cornering, rough road, and a shock load course which included crossing a series of hillside ditches.

It was evident that the final analysis of life expectancy and design efficiency would have to come primarily from strain gage readings. It was felt that locating these gages by judgment alone was pure folly; therefore, Stresscoat was chosen as the gage-locating medium.

A. Stresscoat Operations & Results

Stresscoat strain patterns from static loads of assembly and tire inflation were obtained under controlled atmospheric conditions according to common procedures[3]. Multiple coatings were used on one wheel on the truck as the truck went through a sequence of maneuvers to determine approximately the operating strain levels. This information was then used to plan the proper Stresscoat sensitivity for subsequent tests in which individual wheels were confined to one truck maneuver for pattern separation. Multiple coatings were again used to cope with the varying temperature and humidity and also to provide strain level segregation[4].

Following is a brief account of a typical test, the turning maneuver. On a certain February morning the local Weather Bureau predicted a high of 49° F and a low of 35° F with drizzling rain for the daylight hours of the following day. Four coatings of different sensitivities, namely those which could be expected to give normal cracking sensitivity of about 700 MII strain at temperatures of 44° F, 40° F, 36° F, and 32° F with 100% relative humidity were chosen for use on quadrants of the wheel. This choice was based on the following premises:

1. The test wheel, with the exception of the valve cutout, was circumferentially symmetrical. If the wheel was divided into quadrants and subjected to a constant system of loads as the wheel rotated, then the stress distribution and intensity in the four sections could be assumed to be identical.
2. If the quadrants were coated with different threshold values of cracking strain, such as chosen above, band segregation of strain sensitivity and direction could be obtained. The coating normal for 44° F would show patterns of all strains 700 MII and greater while the coating normal for 32° F would at 44° F show patterns of perhaps 1,800 MII strain and greater. This segregation also would reveal any difference in direction of principal strain at various strain levels on the strain cycle.
3. Furthermore, this spread in sensitivity range would allow for operation at weather conditions differing somewhat from the Weather Bureau prediction.

The wheel was prepared with Stresscoat ac-

FIGURE 3. STRESSCOAT PATTERN IN BEAD SEAT FROM TIRE INFLATION.

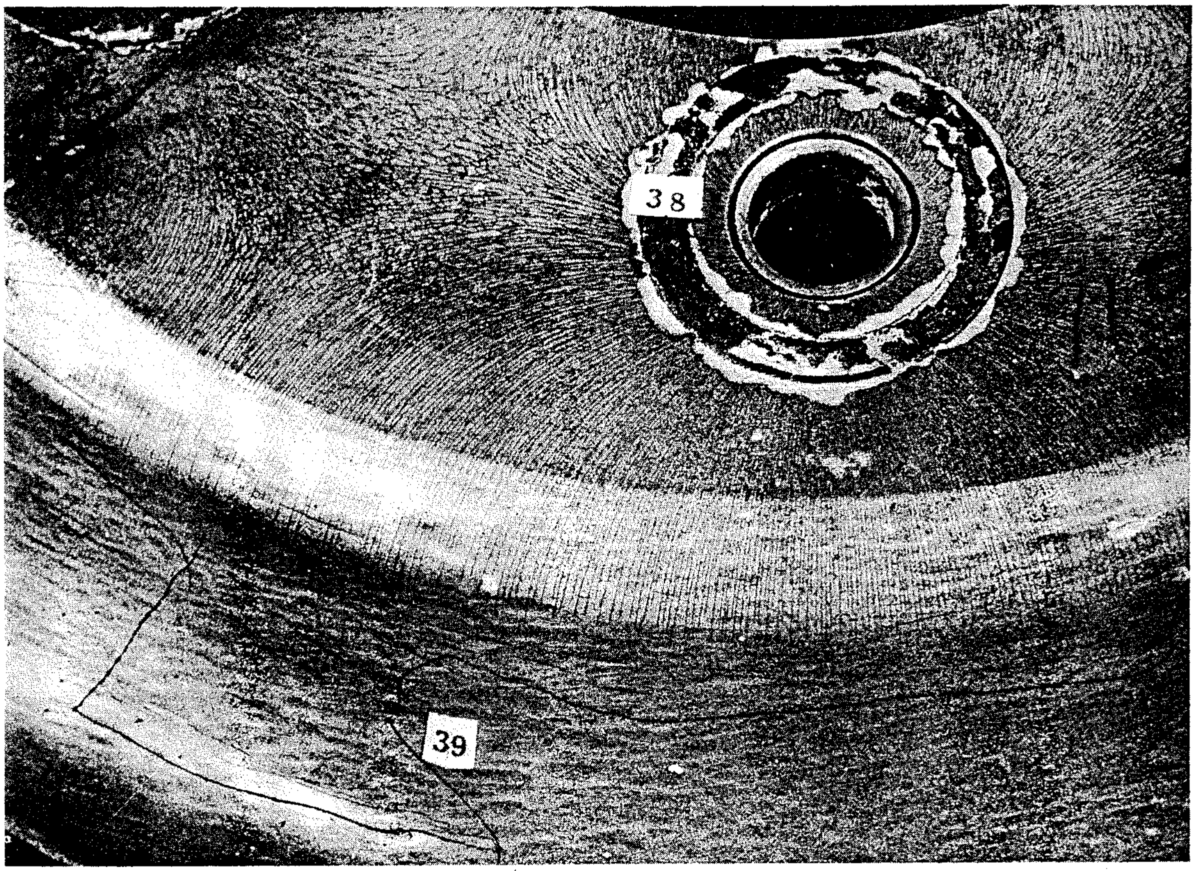

FIGURE 4. FULL PATTERN ON MOUNTING FLANGE.

cording to the manufacturer's recommendations[3]. Removal of the tire chafers* for short lengths provided room for application of the coating in the wheel bead seat, (Figure 3). When the outside atmospheric conditions became right, as checked by calibration strip of the most sensitive coating, the wheel was brought outside from the drying room, mounted on the truck, and allowed to come to the ambient temperature. During this time the truck wheel was held off the ground by lift jack in order not to induce residual strain in the coating. The truck was then run through the maneuver and coatings dyed. Calibration strips of all four coatings were kept under the same conditions as the test wheel throughout the test and then cracked instantaneously as the truck went through a particular maneuver.

Typical Stresscoat patterns are shown as follows: (Location on wheel described by Figure 1).

FIGURE	LOAD or MANEUVER	LOCATION ON WHEEL
3	Tire Inflation	Demountable Flange Bead Seat
4	Full Pattern Run Combining Straight Driving, Turning, and Braking	Mounting Flange
5	Truck Turning (Most Sensitive Quadrant)	Mounting Flange

During the turning maneuver, some sliding of the collar against the wheel mounting flange occurred, causing the flaked coating in Figure 5.

B. Instrumentation

Some 120 SR-4 strain gages were applied to one wheel on the basis of the strain patterns

* A tire chafer is that layer of fabric which is in intimate contact with the wheel at the bead seat and bead radius.

found on the preceding several wheels. These were mostly of the A-7 and A-8 varieties properly protected with Cerese wax. Gages were also installed to measure the vertical bending of the truck axles in an attempt to correlate wheel load with wheel stress. Measurement of static strains due to assembly and tire inflation was made with a Baldwin Static Indicator and a Baldwin 48-gage Scanner Recorder. A Hathaway S12A oscillograph and associated equipment, mounted in a cart on the truck bed (Figure 2), were used in the recording of strains during truck maneuvers.

The measurement of strains in a rotating wheel involves the use of some sort of sliding contact which transmits the strain gage signals undistorted from the rotating wheel to the stationary recording instruments. This was accomplished with the mercury-pool connector shown in Figure 6[5]. The crank-arm on the left is fastened to the wheel and to the rotor of the connector unit. Strain gage leads from the wheel are fastened to rotor terminal posts on the left, and the instrument leads are attached to the stationary terminal posts on top. The rotor comprises a series of 12 knife-edge copper discs mounted on a hollow shaft and rotating in V-channel rings which can be viewed through the shell opening in Figure 6. The rotor shaft was made hollow to accommodate a center shaft so that the connector could be used with either stationary or rotating axles. Figure 7 shows one channel in detail, including the mercury pool through which the disc runs. Note the wet contact surface completely around the disc.

This connector unit also has an adjustable synchronizer dial and a pair of terminals, visible on the right end of Figure 6, which when energized provide a pulse through a shorting

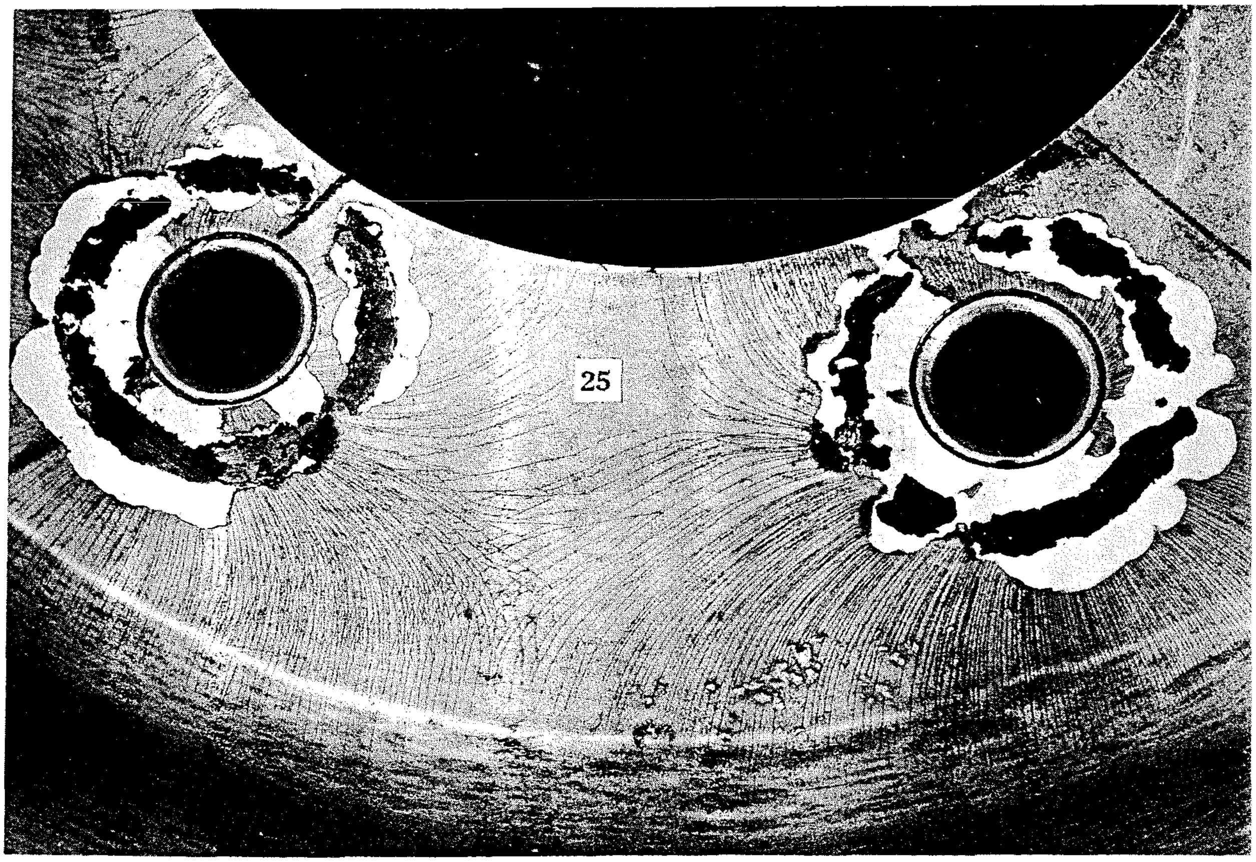

FIGURE 5. MOST SENSITIVE QUADRANT ON MOUNTING FLANGE PATTERNED DURING TRUCK TURNING MANEUVER.

contact once per revolution so that strain signals can be correlated with respect to the wheel's rotational position.

In many tests with this unit using split-bridge operation, i.e. only the active gage going through the slipping contact, there has been no evidence of signal interference from the contact except when vertical accelerations became severe. This was indicated when the unit was first cantilevered directly from the truck axle and the truck run over the shock course. A flexible shaft drive was therefore employed, Figure 2. Strain gage leads were brought through a hollow flexible cable surrounded by a stationary sheath suspended from the truck by shock cord. The cable at the same time served to drive the connector rotor.

Because of the negligible driving torque required, there was practically no rotational lag in the drive and the position indicator could function accurately. Lead wires were brought in and out of the hollow shaft through "T" hydraulic fittings.

C. The Strain Records

The volume of data and records obtained from 120 gages during wheel assembly, tire inflation, truck maneuvers (straight driving, turning, braking, and sharp cornering) on smooth road, washboard road, rough road, and hillside ditches cannot be adequately covered in this paper. Figures 8 and 12 are samples of the records and their interpretation.

Figure 8 shows the records of one gage on the mounting flange obtained while the truck was run through a sequence of maneuvers at the same instrument gain. The tight circle record was made with the test wheel mounted on the front axle. All other records shown were made with test wheel mounted singly on the rear axle. The straight line through the

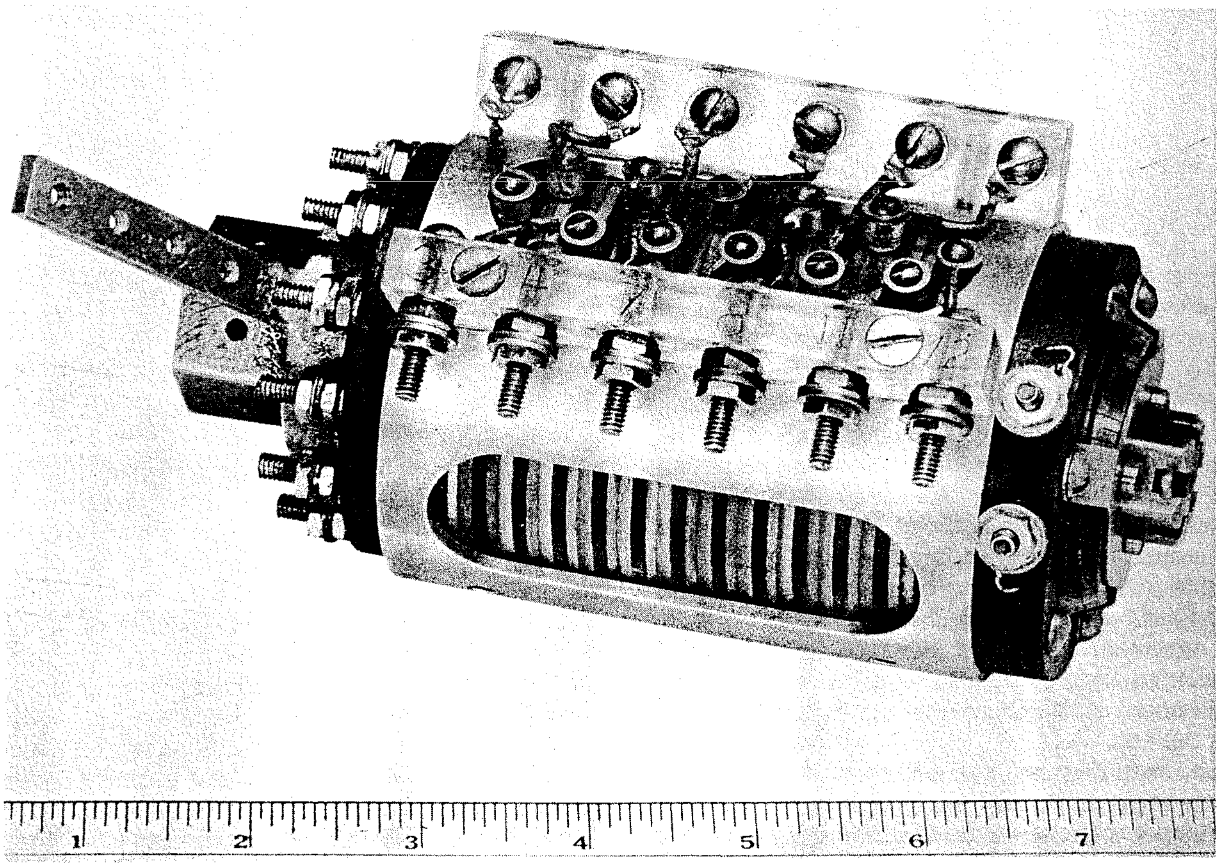

FIGURE 6. 12-CHANNEL MERCURY-POOL CONNECTOR.

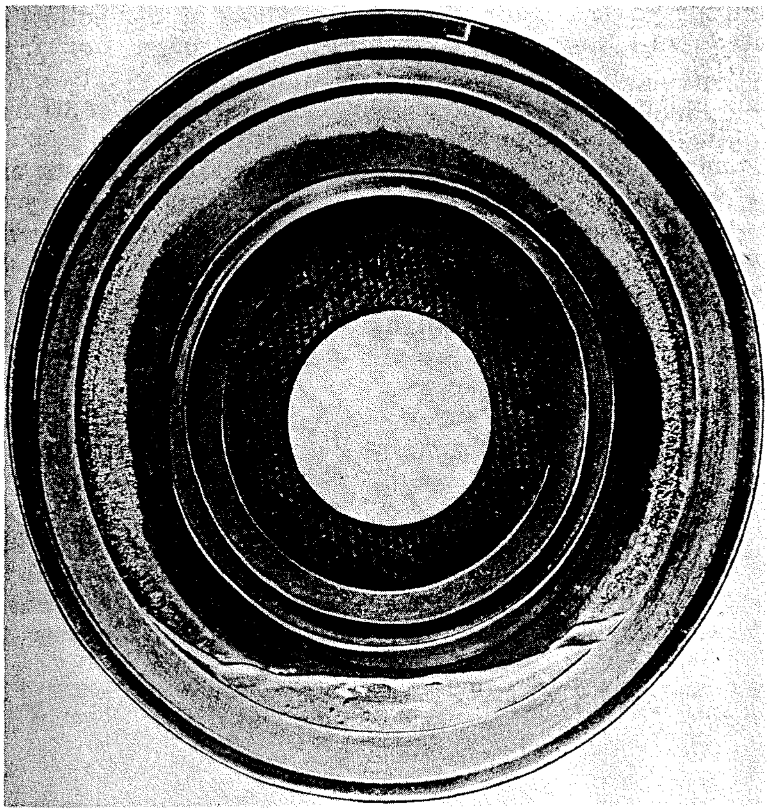

FIGURE 7. CLOSE-UP OF SINGLE CHANNEL OF CONNECTOR.

wheel record represents the level of prestrain from wheel assembly and tire inflation about which the strains from truck maneuvering cycled. "Gages at Load" indicates the instant of time at which the recording gage was in a vertical line between the truck axle and the road. The vertical time-base lines are spaced at $\frac{1}{10}$ second. It is significant to note that the cornering load on the front wheel in a tight circle maneuver provided a strain range in the mounting flange in the order of three times that existing during straight rolling. The axle gages measured the vertical bending of the axle only and were, therefore, not a true measure of wheel load when side load components were present.

On the rough road the axle gage fluctuated between zero load and approximately 2G and on the shock course showed a maximum of 4G with a rebound of the axle to almost 1G negative. After this 4G record, the front axle was bowed severely and the truck bed, where the sand bags were stacked, had collapsed. Movies showed the truck to be momentarily airborne after the impact.

PERFORMANCE EVALUATION

At this point in such a program all that exist are the strain data, which, although interesting, indicate very little regarding wheel performance. The first problem is to get strain translated to stress. This is complicated by the loop-cycling characteristics of the stress-strain relation of magnesium and the lack of sufficient knowledge regarding work-hardening behavior for magnesium. The second problem is to find compatible fatigue data on which to base fatigue damage and life expectancy predictions. In the last few years great strides have been made in the measurement of strains but there remain wide gaps in the knowledge of what those strains mean, especially with respect to the analysis of fatigue. The fol-

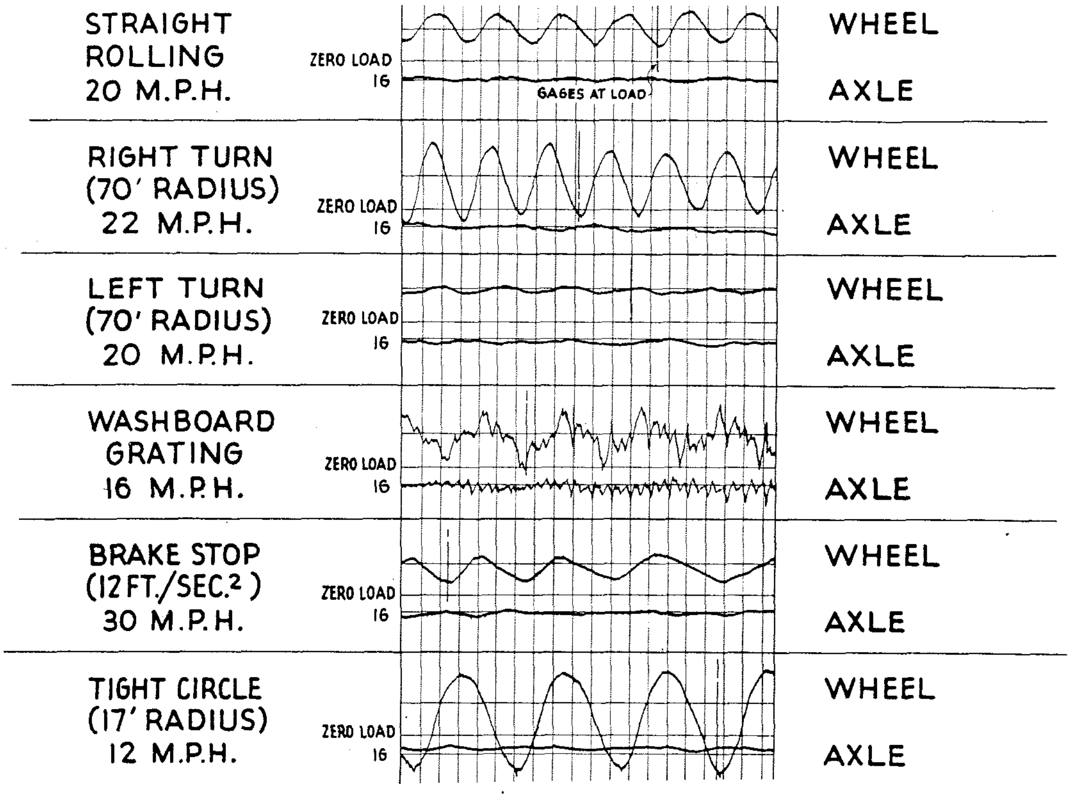

FIGURE 8. SAMPLE RECORD OF STRAIN GAGE THRU SERIES OF TRUCK MANEUVERS.

lowing interpretation to the problem is based partly on published data, partly on some basic studies by Mr. E. H. Schuette of The Dow Chemical Company and the writer, and partly on conjecture. It will doubtless emphasize the need for more fundamental research on the mechanical behavior of materials under cyclic loading.

A. Interpretation of Strain to Stress

The usual stress-strain curve for magnesium must be used with caution. It does define the proportional limit below which strain is converted to stress by the 6,500,000 modulus. However, the stress at the proportional limit is only 6,000 psi, approximately, and above this point things are not very well defined.

As shown in Figure 9, an axially-loaded tensile specimen was cycled between zero load and increasingly larger values of tensile load. It can be seen that immediately after exceeding the proportional limit the specimen fails to retrace the stress-strain curve, but instead shows a series of loops, the secant slopes of which decrease as the maximum strain of the loop increases. In a structure where preloads are present, partial cycling of such a major loop may take place. The stresses of this partial cycle are dependent upon the maximum strain cycle which has preceded it and upon which end of that cycle occurred last preceding the partial cycle. If the partial cycle is small, beginning at one end of a loop, the cycling will be on a 6,500,000 modulus slope because it will be noted in Figure 9 that the first part of each loop side is a line parallel to the original modulus line.

If a specimen is cycled between constant stress limits, it will exhibit a decreasing strain range until that range is related to the stress range by the 6,500,000 modulus, i.e. until the loop closes. If a specimen is cycled between constant strain limits, it requires more and more load range to maintain that cycle. These are work-hardening phenomena exhibited in two ways(6).

Points of high stress concentration or strain gradient tend to cycle at a constant strain cycle for constant load cycle on the structure because of elastic return of the structure. This was demonstrated by measurements on specimens as pictured in Figure 10. Specimen (A) was a tensile specimen which, when loaded with a balanced axial load, was assumed to have uniform tensile strain through its cross-section. Specimen (B) was in geometry and location of strain concentration (the shaded area) similar to a wheel flange. When specimen (A) was loaded to produce 3,000 MII strain and then the load removed, it returned to 1,000 MII strain at zero stress as shown in Figure 9. However, when specimen (B) was loaded such that 3,000 MII was produced at the point of highest concentration in the radius and then the load removed, this concentration point returned to 90 MII, demonstrating the effect of elastic return.

With continued cycling of specimen (A) between the same load limits, the strain range decreased as work-hardening progressed, but the stress range remained constant(6). With continued cycling of specimen (B) between constant load limits, a strain gage at the point of concentration showed that the same strain range was maintained very nearly to failure of the structure. Schuette's work(6) has shown that maintaining a constant strain range required a progressively increasing stress range.

In the case of a large number of gages which must be intermittently recorded on the oscillograph in groups, some gages will experience strain history which does not show up on the records. It is essential, therefore, that this cycling behavior be considered both in the planning and interpretation of the tests to arrive at the proper values of mean stress and stress range. Even then, the mean stress cannot always be defined.

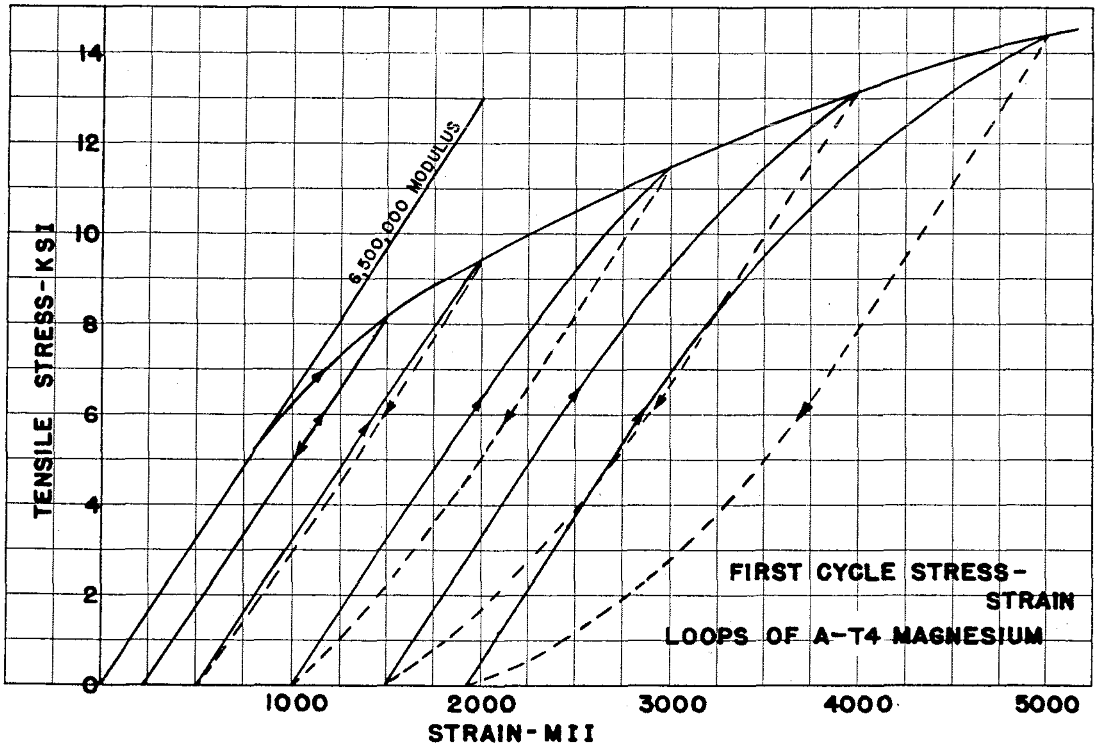

FIGURE 9. FIRST CYCLE STRESS-STRAIN LOOPS OF DOWMETAL A-T4 MAGNESIUM.

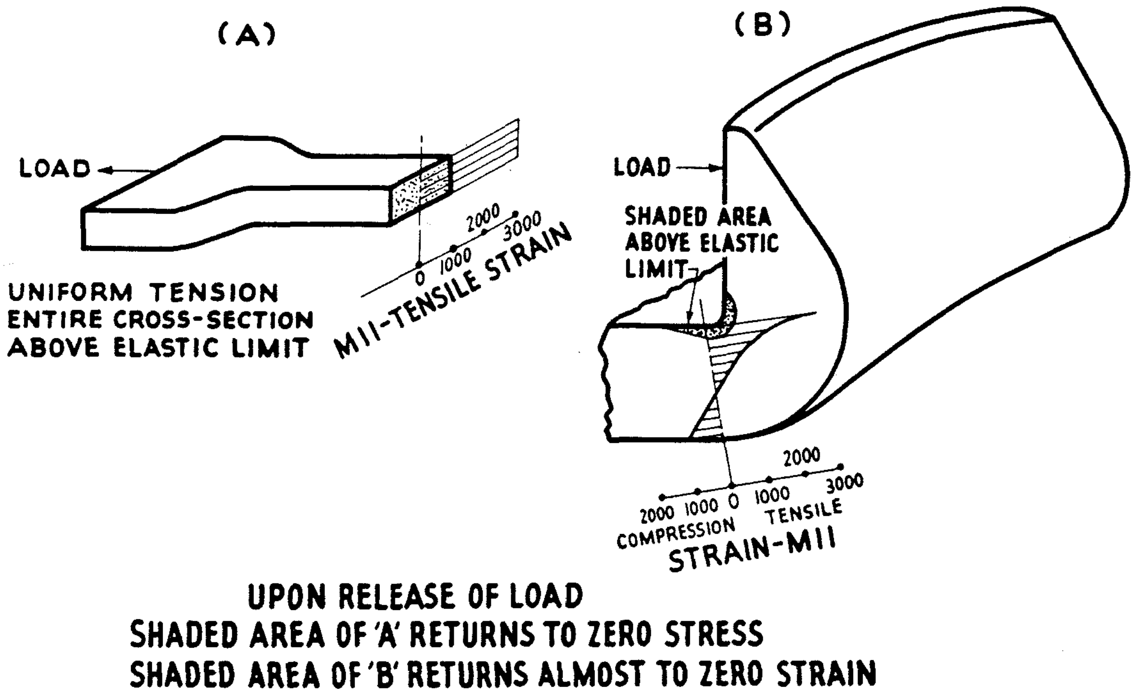

FIGURE 10. ILLUSTRATING STRAIN GRADIENT.

B. Choice of Fatigue Data for Evaluating Interpreted Stresses

This choice is governed by at least the following factors: (1) kind of loading, (2) life expectancy, (3) surface condition of metal, (4) degree of stress concentration, and (5) biaxiality of stresses.

1. Kind of Loading: Plate bending fatigue data available from The Dow Chemical Company were chosen because the strain gage survey of the wheel indicated that primarily bending stresses were involved and also because good correlation of these data with service life had been found to exist on other structures[7]. These data for "as cast" Dowmetal A-T4 were expressed in terms of mean stress and stress range for three values of life expectancy at Stress Concentration Factor equal to 1, Figure 11. There were no data to cover the negative mean stress conditions, so the positive mean data were extended in the same way that such data have been shown for aluminum[8].

2. Life Expectancy: It was estimated that a minimum of 10^6 cycles of the turning and cornering maneuver (found to be the most severe) were required for satisfactory life of the wheel. The goal was set at 10^7 cycles for all stress cycles, however, because it seemed unwise to evaluate on the basis of 10^6 cycles when only a small reduction in allowable stresses would bring them within the endurance limit (see Figure 11).

3. Surface Condition of Metal: It had been shown that the allowable stress range for all magnesium alloys was higher for a machined than for an "as cast" surface[9]. The "as cast" data were chosen as the criterion since machining would be cut to a minimum for economy reasons and those critical areas which would still be machined would enjoy some additional margin of safety.

4. Degree of Stress Concentration: It had also been shown that the fatigue strength reduction factor for cast magnesium alloys was slightly less than the stress concentration

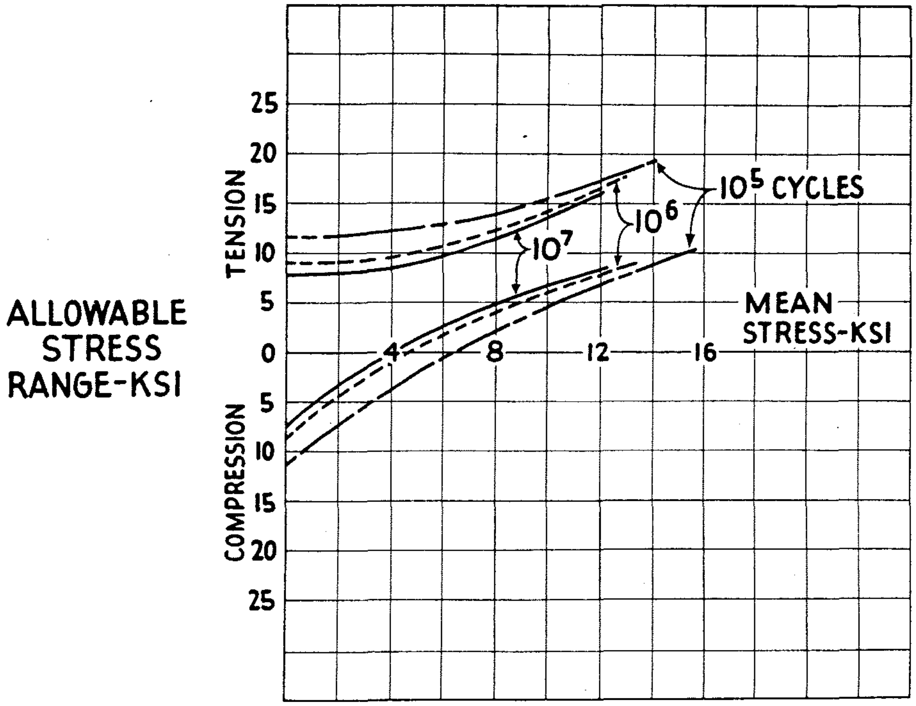

FIGURE 11. FATIGUE DATA FOR DOWMETAL A-T4 MAGNESIUM.

factor(10). Therefore, if the actual concentrated stress was measured or predicted from known studies of similar concentrations, it should be safe to evaluate this stress against fatigue data obtained on flat plates at Stress Concentration Factor equal 1. Since nearly all gages, located by Stresscoat, were of $\frac{1}{8}$" and $\frac{1}{4}$" gage length, it was felt that the actual peak strains existing in concentrations were measured to a fair degree of accuracy where it was possible to apply gages.

5. Biaxiality of Stresses: Hardly anywhere in the wheel was there a true uniaxial stress condition, yet there were no data on the various degrees of biaxiality and their effects on fatigue life of magnesium. The principal biaxial stresses were, therefore, determined as far as possible and evaluated against uniaxial data. Some general agreement has been shown for steel between the fatigue limit under in-phase biaxial stresses and the distortion energy theory(11), although any agreement of the behavior of 24S-T aluminum with this theory was found to be confined to the static stress condition(12).

C. Fatigue Damage Theory

Although the cumulative-damage theory appears to be the most popular method of evaluating multiple-cycle spectra, a cursory examination of literature makes one wonder if there is any reliable theory(13). In the test wheel the strain wave shapes maintained themselves rather closely for all maneuvering loads, the principal change being one of amplitude. Since the premise of life expectancy of 10^7 cycles for the most severe stress condition had already been postulated, there seemed to be no point in considering smaller stress cycles which would naturally fall within the endurance limit.

D. Portrayal of Information to the Designer

The designer needed to know at least the following:

a. Does the design meet the life requirements from a fatigue standpoint?
b. How do preloads (assembly and inflation) affect the fatigue life?
c. To what extent do the various truck ma-

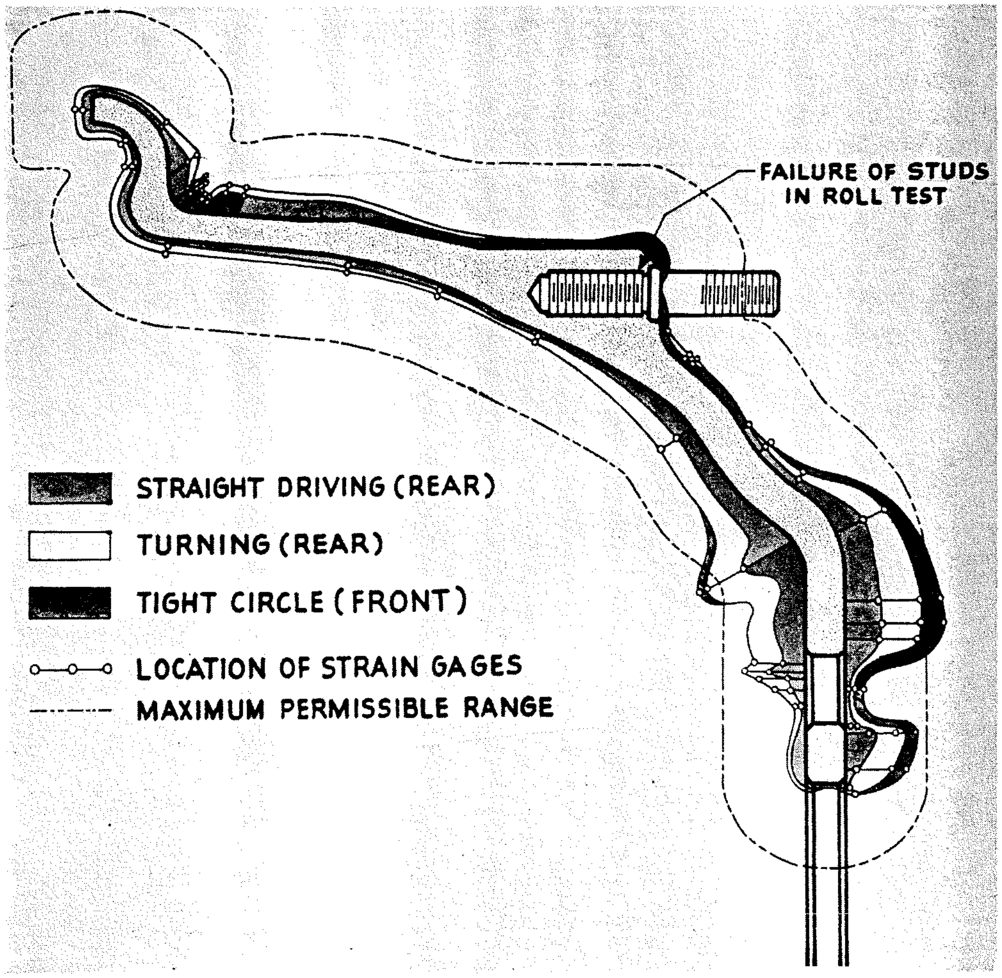

FIGURE 12. GRAPHICAL FATIGUE EVALUATION COMPARING MEASURED STRESS RANGE WITH MAXIMUM PERMISSIBLE STRESS RANGE AT THE SAME MEAN STRESS.

neuvers contribute to fatigue damage?
d. Where can metal safely be removed to reduce weight?

The preload stress, mean stress, and stress range values were tabulated for each gage location and each maneuver. However, this maze of data made the overall objective difficult to grasp; the graphical presentation seemed much more effective. Once the overall picture was understood, individual gages could be studied in more detail. A graphical presentation of the preload stresses, in which stress magnitude was represented normal to the wheel surface, gave at a glance the high and low stress locations and in this case hinted at the weakness in the wheel mounting flange from tightening the mounting nuts, for very little cycling stress added to the preload stress would produce a critical situation.

The fatigue portrayal, Figure 12, was a little more difficult but more informative once obtained. The fatigue evaluation was rated in terms of "Percentage of Allowable Stress Range," which is perhaps more descriptively called "Factor of Utilization" in other references[14]. The measured stresses obtained from a given strain gage show a value of stress range at a certain mean stress. This measured stress range is then some percentage of the allowable stress range at the measured mean stress. Figure 12 also shows the location of failure after 16,000 miles of roll testing at rated load on a flywheel dynamometer.

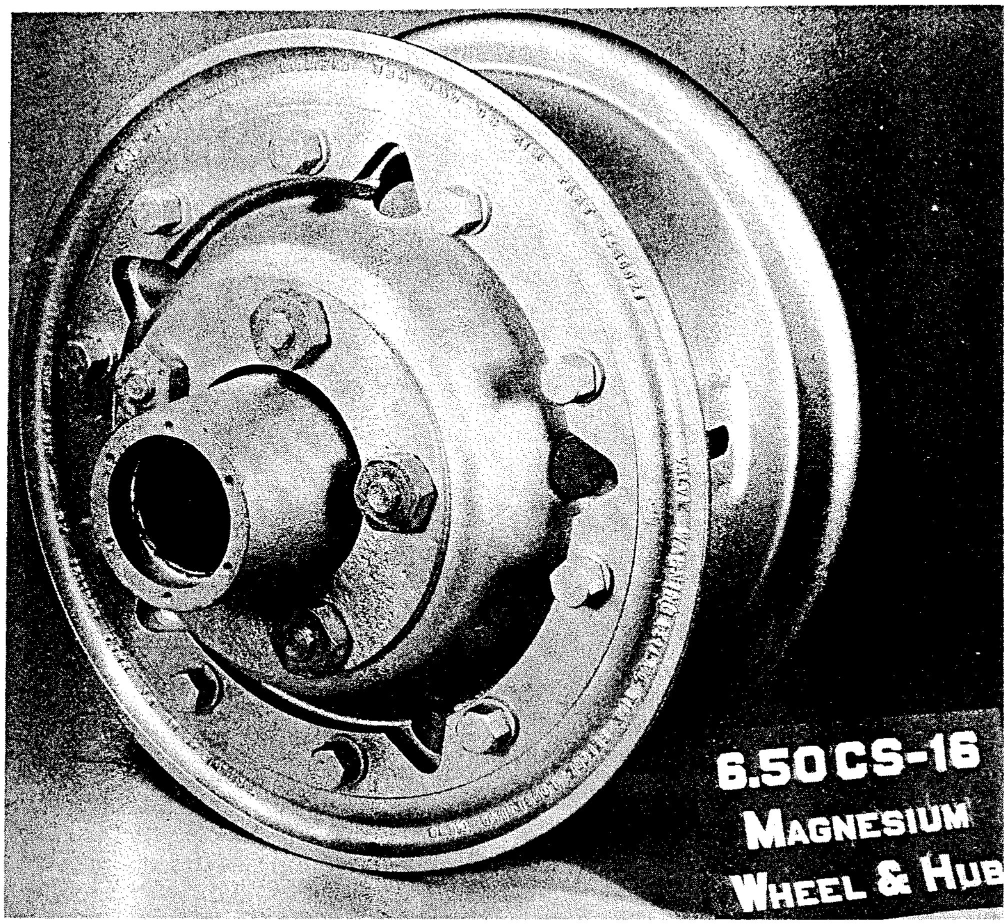

FIGURE 13. A WHEEL DESIGNED ON BASIS OF EVALUATION OF TEST WHEEL.

E. Conclusions Drawn From Testing and Analysis

Because of changing needs, the test wheel was not redesigned in the same size. However, the results of this analysis as summarized in graphs such as Figure 12 provided a much sounder basis for design of the 6.50-16 wheel shown in Figure 13, which achieved a 45% weight reduction over a steel wheel of the same size and type and did run 40,000 miles at considerable overload on a roll test dynamometer without failure.

Some of the more important conclusions from the analysis of the 6.00-20 wheel were:

1. Some sections of the wheel such as the tube well could be lightened considerably and still perform satisfactorily.
2. The collar-type mounting nuts did not distribute the assembly stresses sufficiently.
3. The demountable flange bolts were attached too rigidly to cope with the bending loads imposed on them.
4. Cornering loads imposed the most severe fatigue damage on the wheel.
5. The arbitrary shock load or rough road course did not give reliable damage data using strain gages on the wheel because of the inability to coordinate wheel position with respect to load occurrence. It was impossible to know whether the particular gages recording were in the proper rotational position to receive the maximum strain from the impact. Probably the best alternative would be to measure load components on an instrumented and calibrated

axle or suspension system and then scan the wheel gages in a laboratory test which would duplicate the load components measured on the truck. In any case the peak stresses encountered in several runs across the shock course were not appreciably higher than the peak strains from turning maneuvers and would be expected to occur with much less frequency.

COMPARISON OF EVALUATION METHODS

It seems fairly well agreed among engineers that there is nothing like service testing to failure to really evaluate a structure's performance. However, this approach has at least the following disadvantages:

1. For parts intended for long life performance, this is time-consuming and costly, utilizing vehicles, proving grounds, etc.
2. With the normally expected scatter of fatigue performance, even of accurately processed test bars, a considerable number of such tests is required to tell the true story.
3. If several loads or maneuvers are included in a test, there will be no measure of their relative contribution to the ultimate failure and, therefore,
4. Will provide little in the way of clues for setting up reliable laboratory proving tests.
5. Excessively strong points do not have a chance to make themselves known and, therefore, exist as a weight handicap.

The analytical or experimental stress analysis approach circumvents these difficulties to a large extent, especially in eliminating the ordinary fatigue scatter variable and evaluating the excessively strong points as well as the weak. There is at this point, however, a dearth of information on several phases of this approach such as:

1. A reliable life-expectancy theory.
2. Reliable and comprehensive fatigue data covering biaxial stress conditions.
3. A full understanding of the stress-strain relation of metals in the various modes of cycling.

Furthermore, there is difficulty and sometimes impossibility of instrumenting mating surfaces of metal parts, which often are the sore spots of fatigue failures.

Analytical testing and testing-to-failure methods are complimentary engineering tools, the proper balance of which can only be judged by the characteristics of the individual case. However, the results of the subject analysis would certainly recommend the analytical approach utilizing Stresscoat and strain gages as the initial step in service load evaluation even with the present gaps in methods of interpretation. With this background many of the weak points can be located in a relatively short time and the overall picture of stress distribution is often very helpful in suggesting a remedy for a particular spot because it shows how the stress is being transmitted to that spot. This approach locates possible sources of weight reduction and ways of improving design efficiency. In this case it also showed that any effective laboratory proving of truck wheels should be built around a turning or cornering type of load - a combination radial and side load. After a wheel has been through this experimental stress analysis phase one or more times, it is ready for the test fleet to get the final shakedown especially to evaluate fasteners, mating parts, corrosion and wear.

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