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Laboratory Testing of Full-size Aluminum Bridge

Essais de laboratoire en vraie grandeur sur un pont en aluminium

Laboratoriumversuche an einer Aluminiumbrücke in voller Größe

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Introduction

Under sponsorship of the Reynolds Metals Company, two general types of tests were performed at New York University on a 60-ft. prototype aluminum bridge with concrete floor slab, as follows:

1. Static-load tests with loads producing maximum shears and moments equal to 1 and 2 times design values for the H 20 loading of the American Association of State Highway Officials (AASHO).
2. Repeated-load tests with loads producing maximum moments equal to 1 and $1^1/_2$ times design values for H 20 loading.

In addition, the natural frequency of the bridge was determined experimentally.

The purpose of the tests was to investigate the structural suitability of the bridge for the service for which it was designed. This was accomplished by visual observation as well as by strain and deflection measurements. These tests were a first step in a long-range development program, and the results are being used for improving highway bridge designs on which the Reynolds Metals Co. is working.

Description of Test Bridge

The test bridge (see Fig. 1 and Fig. 2) had three prefabricated, aluminum modular units supported on commercial type (Lubrite) bearings which rested on concrete piers founded on rock. The reinforced concrete slab was, on the average, slightly over $6^1/_2$-in. thick. It was joined to the aluminum modules by means of extruded aluminum shear transfer devices in order to insure composite action. The Z-shape shear devices are shown in place during erection in Fig. 3. All aluminum components were fabricated from a non heat-treatable

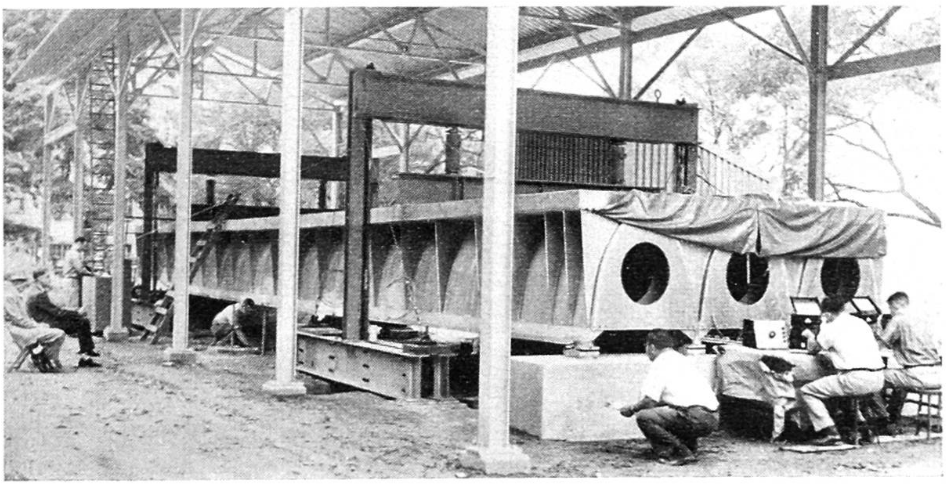

Fig. 1. Static Load Test.

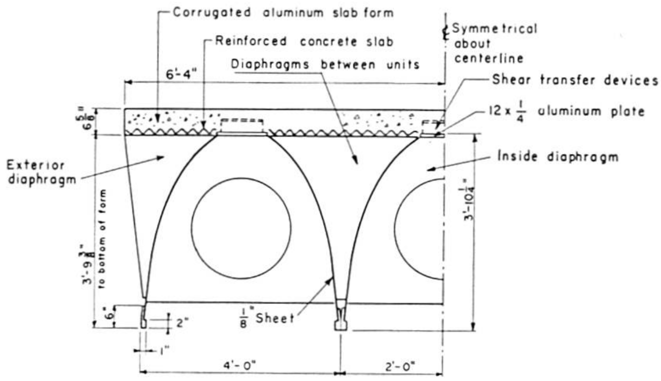

Fig. 2. Half-Section Through Bridge.

aluminum-magnesium alloy designated as 5083. The shear devices and the extrusions which formed the bottom flanges were cold work-hardened to H 112 temper. All other components were made from annealed metal (0 temper).

Each modular unit consisted of curved, $^1/_8$-in. thick, side sheets welded to the bottom extrusions and to a 12-in. wide by $^1/_4$-in. thick plate at the top. A unit had nine inside diaphragms, of $^1/_4$-in. thick plate, connected to it by Huck fasteners. Two of these were over each end bearing and five at intermediate points. Other $^1/_4$-in. diaphragms, more closely spaced, were installed between adjoining units and on the outer side of the exterior units. Adjoining bottom extrusions were bolted together by means of $^1/_4$-in. high strength bolts spaced at 10-in. centers.

Loads were applied to the test bridge by hydraulic rams reacting against structural steel yokes which transferred the ram reactions to anchor rods embedded in rock. Fig. 1 shows the loading yokes in place for a static load test.

Instrumentation

The instrumentation was planned in accordance with the stated purpose, which was to conduct static and repeated-load tests, and to record a limited number of strain and deflection measurements. Vertical deflections of the test

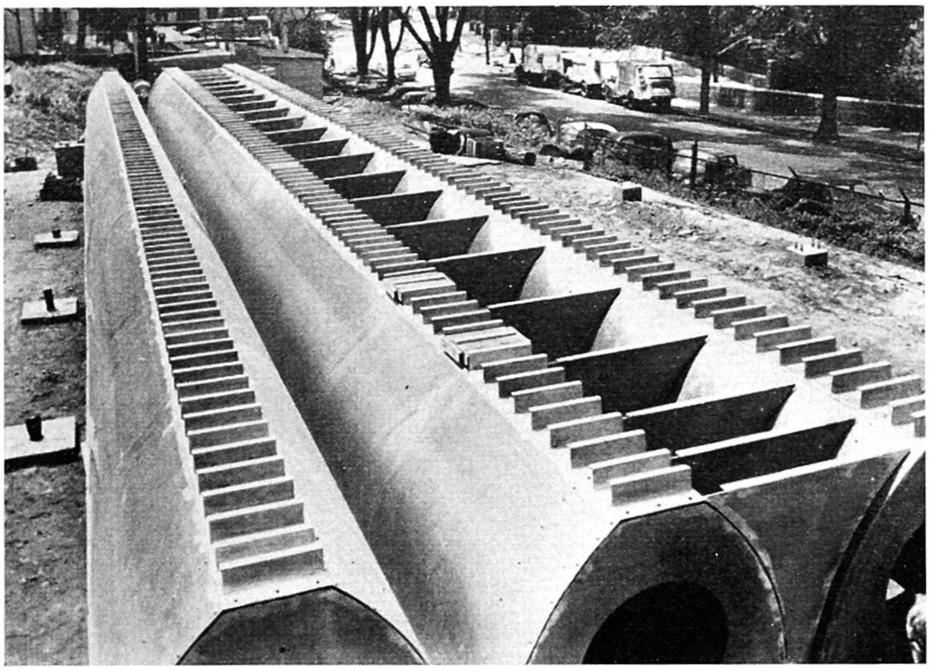

Fig. 3. View During Erection.

bridge were determined by means of a Wild N 2 Level, and longitudinal movements at the expansion end of the test bridge were observed by means of dial gages. Transverse horizontal movements of the bottom extrusions were determined by using plumb bobs hung from the extrusions; but, as maximum transverse movements during the first static tests were on the order of one millimeter, these measurements were discontinued for all subsequent tests.

Strains produced in the test structure by the weight of the concrete slab and by static and repeated loads were measured at selected points by means of Baldwin SR-4 electrical resistance strain gages placed in both uniaxial and rosette patterns. The leads from the gages were wired to switching units, and Baldwin Strain Indicators were used to determine the change in strain corresponding to an increment of load. When the variation of strain with respect to time was desired, as during the monitoring of the repeated-load tests, a strain gage was connected to a Brush Universal Analyzer and the data plotted on a Brush Paper Strip Recorder.

Static Load Tests

The following four types of static load tests were made:

1. Concrete slab on the aluminum modular units.
2. Two symmetrically applied loads on the composite structure, resulting in simultaneous design values, or multiples thereof, of bending moment and shear.
3. Eccentrically applied loads on the composite structure.
4. Single applied load at mid-span of the composite structure.

Concrete Slab on Aluminum Modular Units

To observe the behavior of the aluminum structure as the concrete was placed, selected gages and scales were monitored. The difference between the final and original sets of readings was considered as the effect of the weight of the concrete slab on the aluminum structure. A comparison between measured and computed deflections, and between measured and computed strains showed good correlation.

Two Symmetrically Applied Loads

The live loads were applied, as shown in Fig. 1, by means of hydraulic rams symmetrically positioned on transverse distribution beams. Thus the force was distributed essentially as a line load across the width of the deck. The loads were placed 12 ft. 2 in. from each end bearing so as to produce vertical shear and bending moment values which would be proportional to the design shear and design moment respectively. As used herein, design shear and design moment are the maximum values produced in a one-lane, simply-supported bridge by a 20-ton truck, together with impact effect, as defined by the current AASHO specifications.

Computed theoretical values of deflections, stresses, and longitudinal movements were based on the following assumptions:

1. There was complete composite action between the concrete slab and the aluminum structure (the ratio of modulus of elasticity of aluminum to that of concrete was taken as 3.5).
2. The load applied through the distribution beam was shared equally by the three modular units.

Fig. 4 shows the vertical deflection at the centerline of the span as the load was increased to 2 times design value and then removed. The plotted values, obtained by averaging the measured deflections at the four lines of extrusions, define reasonably smooth curves during the loading and unloading stages. Up to approximately 1.5 times design load the measured deflections varied almost linearly with load but lagged in comparison to the computed

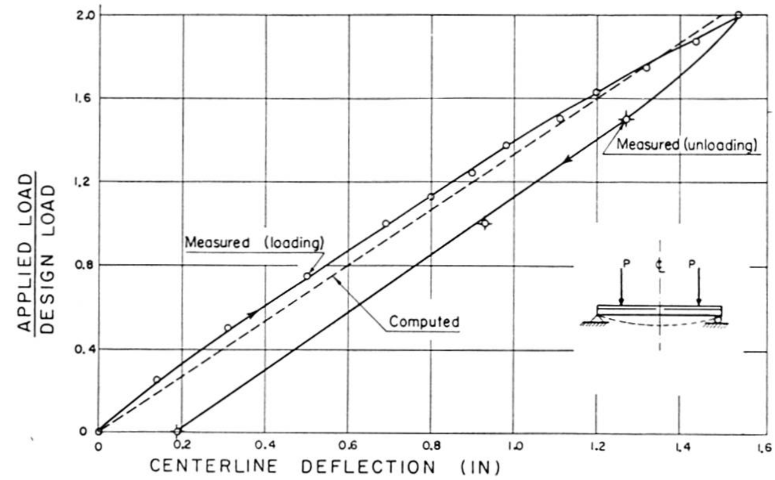

Fig. 4. Centerline Deflection.

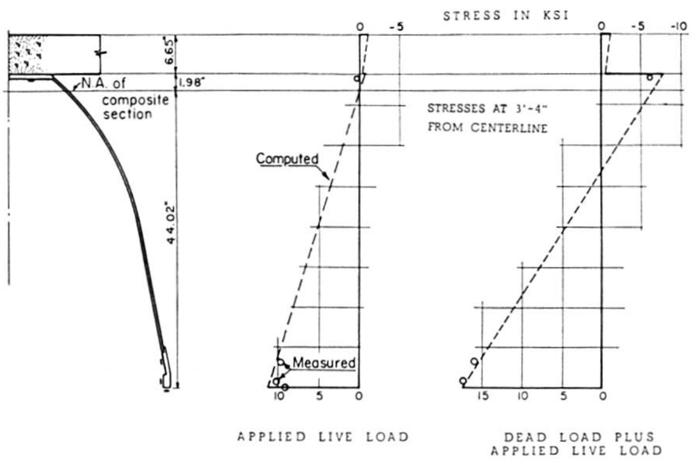

Fig. 5. Stresses at Two Times Design Moment.

values. At loads above 1.5 times design value, the deflections increased nonlinearly with load so that at the maximum of 2.0 times design value the measured vertical deflection was slightly larger than the computed value. As reported subsequently, the lag in measured deflections was due principally to end bearing friction.

Comparison of measured with computed values of longitudinal movement showed good correlation, but with a lag of almost 10 percent in the measured values throughout the loading range. During the unloading stage the lag of measured movement was still more pronounced. As in the case of vertical deflections, this was due principally to the frictional restraint of the sliding detail at the expansion end.

Computed bending stresses and those deduced from measured strains, in kips per sq. in., are shown in Fig. 5. In the bottom extrusion the measured values are consistently lower than the theoretical values, with a maximum difference of approximately 10 percent. The strain gage readings on the underside of the top plate, although somewhat erratic because of the very low level of stress, are consistent with the anticipated position of the neutral axis.

Some evidence of structural distress was observed as the applied load was increased from $1\,^7/_8$ to 2.0 times design moment and shear. There was some local yielding and buckling in the $^1/_8$-in. sheet over the supports. The buckles were of limited size ($^1/_{16}$-in.) and probably represented a readjustment of an unfavorable local condition.

Eccentrically Applied Loads

To make this test, only the hydraulic ram on the west portion of each of the two distribution beams was used to apply load. The measured deflections and stresses varied almost exactly linearly across the structure from a minimum value at the most easterly extrusion to a maximum value at the most westerly extrusion.

The primary objective of the static load tests was to study the over-all behavior of the test structure as reflected in changes in deflection and strains. The possibility of buckling of the curved sheets under load was recognized; however, due to the large number and variety of buckles in the structure as erected, no serious attempt was made to monitor all of the panels for new or modified buckles under applied load.

The three modular units, as received, contained a small number of large buckles in the curved sheets. After the erection of the modular units and the installation of the external diaphragms which divided the structure into 23 panels, additional buckles of varying size, shape and orientation were formed. A survey revealed that the six curved sheets contained as few as 3 buckles of noticeable size per sheet and as many as 22 per sheet. Although it was difficult to measure the size and amplitude of these distortions with any degree of accuracy, there were some which dished in or out as much as $^1/_2$ in.

Later, during the repeated-load program, it was noted that some of the buckled areas were "breathing". Apparently these buckles were straightening out elastically, under the effect of the diagonal tension stresses introduced by the applied load, moving back to their dead load configuration upon release of the load.

During the eccentric load test there occurred an incident that raised some questions regarding the stability of the panels under high shear loading. While readings were being taken under an eccentric load of $^7/_8$ of the design value, an observer, leaning with his hand on a curved panel, produced a depression of approximately $^1/_2$ in. Apparently the buckled shape was stable, since no further change was detected as the load was increased to 1.0 times design load and then released.

Special Studies with Single Load at Mid-Span

During the repeated-load tests (discussed later), there were periods when cycling was suspended, and it was decided to utilize the loading set-up (single line-load at centerline) to investigate the effect of sliding friction at the bearing and the effect of using a line load rather than a simulated wheel concentration.

To study the effect of type of expansion bearing on deflection and on longitudinal movement, steel rollers on suitable bearing plates were substituted for the Lubrite plates. With roller supports the lag of measured values was eliminated. In addition, noises and jerky movements due to end restraint were essentially eliminated.

In all previous load tests a distribution beam, which rested on the roadway slab for its full width, had been placed under the ram. To simulate a wheel concentration, it was decided to use a steel plate. As it was inconvenient to remove the distribution beam, it was raised and the plate was placed between the beam and the roadway. There was no appreciable difference in behavior with the plate from what had been observed with the distribution beam.

Strains in the concrete slab were determined by means of suitably moisture-proofed SR-4 strain gages. Measured values were approximately 25 percent lower than computed values.

Repeated-Load Tests

After consultation with Mr. E. L. Erickson of the Bureau of Public Roads, the following program of repeated-load tests was adopted:

1. 50,000 cycles at 1.0 times design moment.
2. 750,000 cycles at 1.5 times design moment.

In all cases the load variation during cycling was from dead load to dead load plus live load. Load was applied by a single hydraulic ram acting on a distribution beam at mid-span.

Test Procedure

The hydraulic loading system was designed and built to apply a predetermined maximum force at the ram irrespective of any vertical movement of the bridge due to temperature change. Periodic checks and adjustments were made.

To provide a continuing check of the response of the structure, the operators monitored a selected group of strain gages, dial gages, and level targets. The readings were taken once each hour, and were followed immediately by a visual examination of the aluminum structure and the concrete deck for any signs of distress. After it became evident that fatigue was causing damage, greater emphasis was given to the visual inspection, and critical areas were kept under careful surveillance in order to detect cracks at an early stage of development.

Tests with Original Extrusions

The 50,000 cycles at 1.0 times design moment were completed without incident. After 360,595 cycles at 1.5 times design moment a crack was discovered. It had progressed through an interior bottom extrusion at mid-span and gone upward into the $^1/_8$-in. curved sheet for a distance of approximately 16 in., almost to the mid-height of the aluminum module. Fig. 6 is a photograph, with the interior diaphragm removed, showing the full extent of the crack. Note its progression through three holes in a vertical line, starting at the $^1/_4$-in. hole in the bottom extrusion.

A 6-in. wide section of the bottom extrusion and a 4-in. wide by $7\,^1/_2$-in. high portion of the curved sheet was cut out to remove the bulk of the crack. The balance of the crack in the sheet was enlarged with a saw after a hole

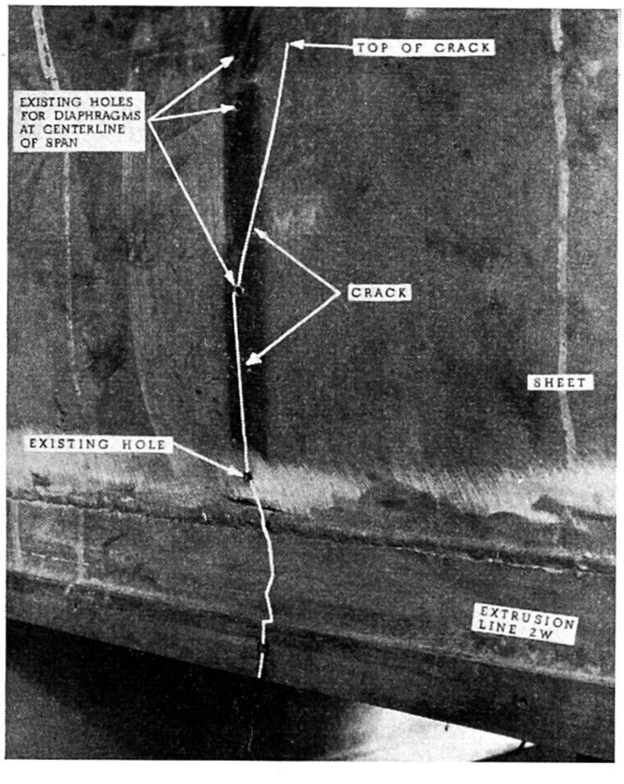

Fig. 6. Crack No. 1.

had been drilled at its upper extremity. Matching patch plates were prepared, positioned, and then welded using the inert gas shielded consumable-electrode process. The completed repair, with additional reinforcing plates for the bottom extrusion, is shown in Fig. 7. In order to replace the interior diaphragm that had been removed, portions of the weld seam were ground down.

Two other cracks, located within 20 in. of mid-span, were discovered before the sponsor decided to replace the bottom extrusions. The second crack occurred 47,045 cycles after the first and originated at a hole in another interior bottom

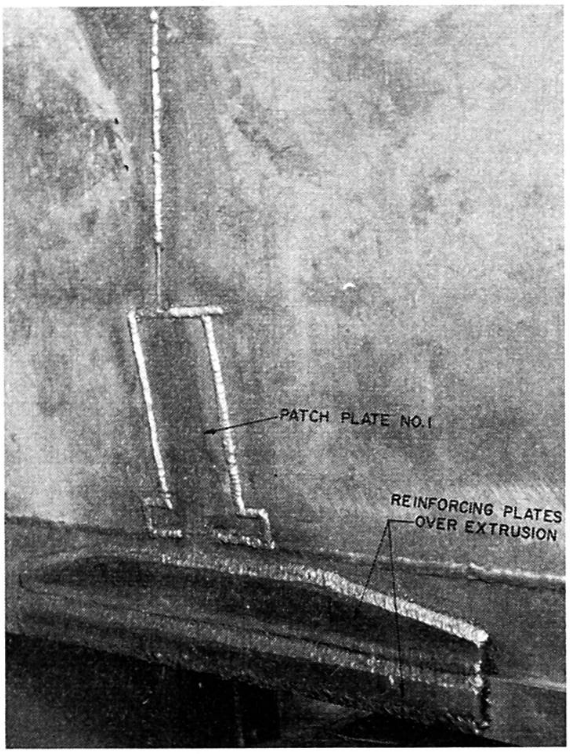

Fig. 7. Repair of Crack No. 1.

extrusion. It was repaired in a manner similar to that used for the first crack. In addition, 53 holes in the central portion of each extrusion were drilled to $^1/_2$-in. diameter and reamed. Of these holes, the 21 closest to mid-span were then plug welded. Due to the limited size of opening in proportion to depth, it was difficult to obtain full weld penetration. The third crack, working its way through a plug-welded hole in still another interior extrusion, forced a shut-down after an additional 39,760 cycles.

Tests with New Extrusions

After the third crack, the sponsor decided to discontinue the practice of making repairs as they became necessary and instead remove the central

49 ft. 6 in. of the bottom extrusions and replace them with others of a new design in which all holes were eliminated. Extrusions on interior lines were to be single units rather than pairs.

It was recognized that the test structure would then consist of two groups of parts with different loading histories. The new extrusions would have no history of repeated loads, while the remainder of the structure would have sustained 50,000 cycles at 1.0 times design moment and 447,000 cycles at 1.5 times design moment. In addition, there would be various difficulties involved in making such a major repair, but nonetheless the sponsor considered it preferable to replace the extrusions. A new extrusion is shown in Fig. 8 adjacent to the pair of extrusions it replaced.

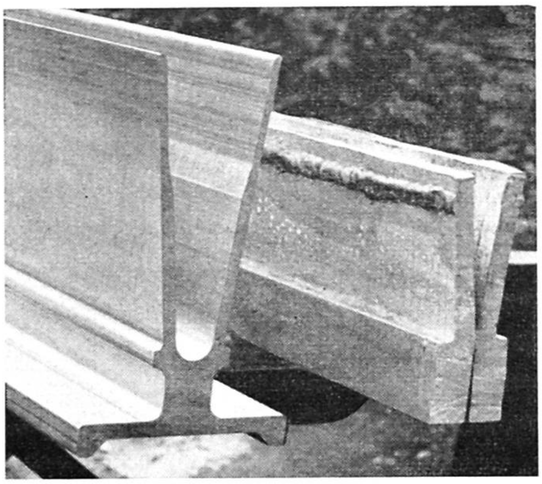

Fig. 8. New and Original Extrusions.

The plan was to raise the structure so as to relieve a designated portion of the dead load bending stresses in the structure, make the repair, and then restore essentially the same dead load stress conditions into the modified structure by removing the lifting force. The particular scheme devised incorporated an arrangement which, in order to keep the working area under the bridge as clear as possible, would permit lifting from above rather than pushing from below. Six $1\,^1/_4$-in. holes, three on each of two transverse lines, were drilled through the concrete slab and the top aluminum plates in order to insert hanger rods. Two banks of three hydraulic rams each were arranged so that lifting loads could be applied gradually to the structure along the two transverse lines.

The edges of the curved sheets took an irregular sinusoidal shape in the transverse direction when the extrusions were removed by sawing. They were eventually straightened out when the replacement section was fitted up and welded. Attention is called to the fact that the sawed edges were not ground smooth.

On the exterior lines, the lapped joint between the sheet and the extrusion was exposed so that both seams were accessible. A continuous fillet weld was made along the top of the extrusion. Later, to eliminate the possibility of cracks starting at the cut edge of the sheet, it was decided to join the lower edge of the plate to the side of the new extrusion by means of a similar weld. Along the interior lines, the rough edges of the sheets were inaccessible and could not be welded. Furthermore, since these edges were behind the stems of the new extrusions, they were hidden from view.

The junctions between new and existing extrusions were spliced using a combination of butt welds and strap plates. Rather large distortions were observed on the curved sheets of the panels in which the splices were made. However, except for some minor crater cracks in the welds, the splices and the affected sheets showed no signs of distress during the balance of the repeated load tests.

Before the additional 302,600 cycles required to complete the program were applied, it was necessary to stop testing six more times in order to repair cracks which developed. These were all located on one line near mid-span, in the vicinity of the longitudinal weld seam.

Analysis of the cracks indicates that they can be classified into two types. The first type is a crack in the weld seam of a previous repair and is due to a variety of reasons, including lack of penetration, removal of weld section, and locked-in stresses. The second type is a vertical crack which appeared at the longitudinal weld seam, apparently isolated, but which is essentially an extension of a crack in the sheet due to a stress raiser in the form of an existing hole.

The repairs made can be classified into three types. The first type, similar to the repairs made when the old extrusion was in place, consisted of cutting out the crack, welding the seam, and adding reinforcing plates. The second type involved cutting out the crack and rewelding the seam with a butt weld. In the third type a patch plate was inserted and butt welded after the area around the crack was removed. No repair of the first type was involved in a subsequent failure, whereas cracks did reappear in both of the other types of repair.

General Assessment of Cracks

All of the serious cracks that developed in the structure involved some sort of stress raiser which eventually led to distress under repeated load. The original stress raisers were the holes in the bottom extrusions. As the result of unsatisfactory repair of the cracks induced by these holes, new stress raisers were introduced, and these, coupled with poor weld penetration in some instances, resulted in the formation of still other cracks. In no case was a crack observed that was not due to one of these causes.

Fatigue Tests on Tension Specimens

Fig. 9 shows three laboratory specimens that were subjected to repeated load from approximately 9,000 psi to approximately 18,000 psi. This stress range corresponds roughly to dead load and dead load plus 2 times live load. The left-hand specimen, containing a $^1/_4$-in. drilled hole, underwent 380,000 cycles before it cracked. The results compare well with the history of crack number 1 although the cycling of the specimen was at a higher stress level. The middle specimen, which had a drilled hole reamed to $^1/_4$ in., underwent 890,000 cycles before cracking. The hole was then enlarged to $^1/_2$ in. and filled by welding, and the specimen underwent an additional 645,000 cycles before cracking. The specimen on the extreme right was drilled and reamed to $^1/_2$ in. After more than 2,000,000 cycles no crack was observed.

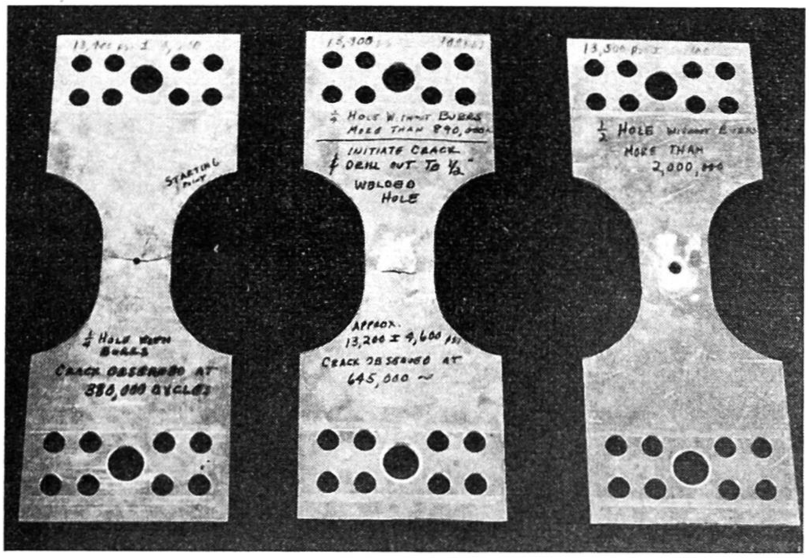

Fig. 9. Fatigue Specimens.

Experimental Determination of the Natural Frequency

A sack of sand, weighing approximately 75 lbs., was lifted 11 ft. above the center point of the bridge deck by a rope and pulley arrangement and then dropped. The resulting vertical vibrations were converted into electrical signals, amplified, and recorded on a paper strip recorder.

Based on the average of measured wave lengths and the known paper speed, it was found that the value of the natural frequency was 4.5 cycles per second, or 270 cycles per minute. For an idealized beam structure with flexural properties corresponding to those assumed for the bridge structure, the theoretical natural frequency is 5.1 cycles per second. The difference of approximately 12 percent is considered reasonable in view of the presence of damping, including the effect of restraint at the expansion end.

Summary

A welded aluminum prototype bridge was subjected to static and repeated load tests in order to determine its structural suitability for use on highways. No signs of distress, except for some local yielding and local buckling over the supports, were observed under static loads. The measured strains and deflections were in general what would be expected on the basis of theory.

The program of repeated-load tests included the application of 50,000 cycles at 1.0 times design moment, and 750,000 cycles at 1.5 times design moment. Before 448,000 cycles at 1.5 times design moment were completed, three cracks were discovered. All three cracks appeared to be due to the presence of holes drilled in the bottom extrusions to accommodate bolts which joined adjacent modules at their lower edges.

The first two cracks were repaired, but after the third crack the bottom extrusions were removed and replaced with others of a new design with all holes eliminated. Before the prescribed program of repeated-load tests was completed, six additional shutdowns were made in order to repair cracks. All of these cracks can be traced to the unsatisfactory repair of a previous crack or to holes that were present in the structure as erected.

Résumé

Un prototype de pont soudé en aluminium a été soumis à des essais de charge statiques et répétés, essais destinés à montrer si l'on pouvait utiliser de tels ouvrages sur les autoroutes. Aucun signe d'épuisement ne se montra lors des essais statiques, à part de légères déformations plastiques locales et un voilement local au droit des appuis. En général, les allongements et les flèches concordaient avec celles données par le calcul.

Le programme des essais à l'endurance comprenait 50 000 cycles pour la sollicitation de service réglementaire puis 750 000 cycles pour une sollicitation de 50% supérieure. Près du 448 000e cycle de la seconde série, on découvrit trois fissures. Toutes ces fissures semblaient dues aux trous percés dans les profilés extrudés inférieurs, trous qui servaient à l'assemblage des éléments contigus à l'aide de boulons.

Les deux premières fissures furent réparées. A l'apparition de la troisième, on enleva les profilés inférieurs et on les remplaça par un nouveau profil sans trous. Avant d'atteindre le nombre de cycles prévu par le programme, les essais durent être interrompus six fois pour effectuer des réparations. Toutes ces fissures provenaient d'une réparation insuffisante des dommages précédents ou de trous percés dans l'ouvrage primitif.

Zusammenfassung

Um die bauliche Eignung einer geschweißten Aluminiumbrücke als Straßenbrücke zu analysieren, wurde diese statischer und wiederholter Belastung unterworfen. Abgesehen von leichten lokalen plastischen Formänderungen und örtlichem Ausknicken über den Auflagern, wurde unter ruhender Belastung kein Erschöpfungszeichen beobachtet. Im allgemeinen entsprachen die Formänderungen und die Durchbiegungen den theoretisch berechneten Werten.

Das Programm der Prüfung auf wiederholte Belastung umfaßte 50000 Lastwechsel unter dem 1,0-fachen Bemessungsmoment und 750000 Lastwechsel unter dem 1,5-fachen Bemessungsmoment. Vor dem Erreichen von 448000 Lastwechseln unter dem 1,5-fachen Bemessungsmoment wurden drei Risse entdeckt. Alle drei Sprünge schienen ihre Entstehung den Löchern in den unteren Strangpreßprofilen zu verdanken. In diesen Löchern waren die Bolzen eingesetzt, die die nebeneinanderliegenden Elemente verbanden.

Die ersten beiden Risse wurden repariert. Nach dem dritten Riß wurden die unteren Strangpreßgurte abgetrennt und durch ein neues Profil ohne Löcher ersetzt. Ehe das vorgesehene Lastwechselprogramm erfüllt war, mußte der Versuch noch 6mal zur Vornahme von Reparaturen unterbrochen werden. All diese neuen Risse konnten auf ungenügende Reparaturen der vorangegangenen Schäden oder auf Löcher in der ursprünglichen Konstruktion zurückgeführt werden.