Design and Shape Analysis of Cast Steel Guardrail Posts

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• THE INCREASING number of fatal accidents resulting from failure of bridge guardrail post systems has focused attention on a serious highway design problem. With ever-increasing traffic on highways, particularly expressways, this problem requires immediate attention to developing a fail-safe guardrail system. This is no small task as there are many points to be considered.

The nature of the problem was brought out early in discussions of the Bridge Castings Task Force Committee of the Steel Founders' Society, which is concerned with problems regarding use of steel castings in bridges. This group gathered as much information and known data as possible as a foundation on which to begin work, but surprisingly little was available at the onset of the investigation due to the fact that guardrails apparently had been designed from a decorative rather than protective standpoint. However, thanks to the cooperation of other groups, the basic problems involving guardrail failures were defined.

The problem is broken down into main parts and briefly discussed from the standpoint of information available initially and then the engineering approach or method being used to work out a solution to the post design.

1. What are the direction and magnitude of forces involved when an automobile hits the guardrail at high speed? To date, it appears there is no source of information on actual forces involved; however, it has been determined that a car traveling at 65 mph will hit the rail at an angle between 20 deg and 30 deg with the road, approximately 23 in. above the road surface. Buses and trucks are less involved in guardrail accidents, and the forces involved with this type of vehicle appear to be too great for practical solution; therefore, it was decided to consider only automobiles.

2. What is the best design shape for the rail post to withstand the forces? Presently, other than concrete, most posts are basically H- or I-beam shapes, which are strong in direct loading but weak in torsional loads.

3. What material is best suited to withstand the forces once design shape has been established? The physical properties of cast steel lend themselves ideally to the fail-safe principle involved with guardrails, particularly the high elongation factor which permits extreme yielding before complete failure occurs.

4. What immediate steps can be taken to strengthen existing post designs being used on new construction or as replacements? This required an evaluation of existing designs to determine the strength and location of high stressed areas, then redesigning these areas for maximum strength.

As always, the cost factor is present. It leads into too many facets for this report, but consideration of cost in proportion to safety is necessary. These basic problems required the establishment of a two-phase engineering program.

Phase one was to evaluate present bridge post designs, determine critical stress level, correlate designs with strength of the various materials, and establish a data base line for further design development. This phase has been completed and a detailed report is on file at the Steel Founders' Society of America and in the library of the Highway Research Board, Washington, D.C.

Phase two was to develop optimum cast steel bridge rail post design.

Phase one included a castability analysis, as the design shape literally controls the castability of a part. Ideally, the design shape should be structurally sound and compatible with good foundry practice. Experience has shown that when this ideal is achieved the quality of cast steel parts is assured when produced by any reputable steel foundry. This paper deals with the findings of phase one as a program of gathering engineering data for a foundation for phase two, which is engineering and development of a fail-safe cast steel post with a castable shape to assure quality as spelled out in the Steel Founders' proposed specifications.

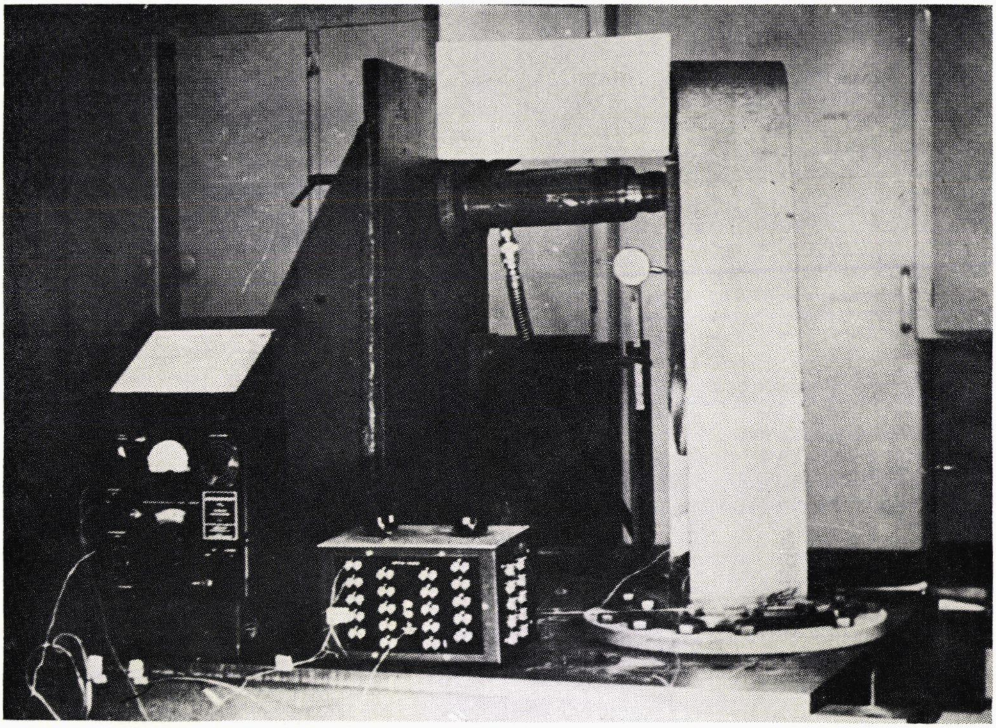
An important engineering procedure, selected to establish design data, was conducting static experimental stress analysis on the present bridge rail post designs, utilizing the tools of brittle lacquer and SR-4 strain gages. Ideally, the best method of testing is under actual conditions, but the cost at the time was prohibitive. Therefore, a method of loading the rail post statically that would simulate actual loads and result in obtaining as much design information as possible was adopted.

A static test fixture was built to accommodate the anchoring or bolting of various types of cast posts with a hydraulic load applied at 23 in. from the base surface. The fixture (Fig. 1) permits loading of the post at 10-deg increments from the 20-deg position, which is torsional load, to the 90-deg position, which is direct load on the post. Several posts of H, I and channel shapes of one, two and three rail heights of different materials were tested for a total of 20 posts used in testing.

EXPERIMENTAL STRESS ANALYSIS

Stresscoat is a brittle lacquer that is sprayed on a properly cleaned and prepared specimen and is cured at 100 F for a minimum of 12 hours. During the time of testing the temperature and humidity are controlled for the coating used. The temperature and humidity was selected to result in a coating sensitivity of 500 to 700 μ-in. (micro-inches) of stress. When the load was applied to the post casting and the strain level reached the sensitivity of the coating, the brittle coating cracked at 90 deg to the maximum principal tensile strain. By loading at increasing increments it was possible to locate the high stress points and also determine the stress distribution with great accuracy. A casting of each post design tested was stresscoated, one each for the 20-deg and 90-deg direction of loading, in order to keep the indicated strain patterns separate. The stresscoat patterns aided in gaining a better understanding of the design shape factor involved. Typical stresscoat patterns on a guardrail post are shown in Figure 2.

Stresscoat patterns showed a stress concentration in the fillet junction of the bottom plate to the front flange in the H-section post design. Also, there were some pre-stress indications in the bolting areas, due to the bottom plate of the steel cast-



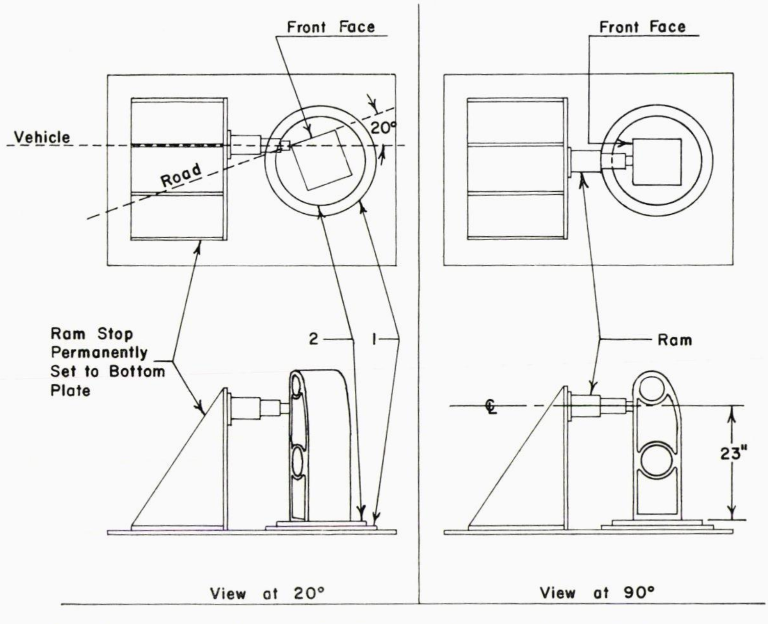


Figure 1. Test setup for conducting static experimental stress analysis.

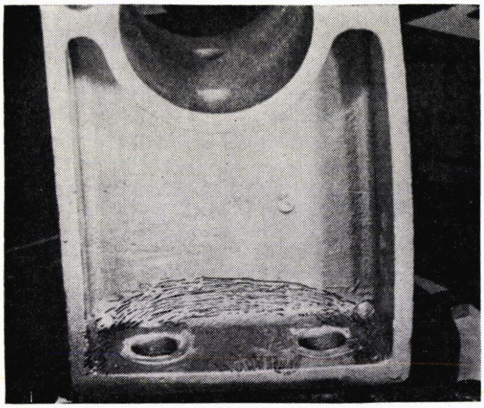


Figure 2. Typical brittle lacquer patterns indicating high stressed areas.

ing not being flat, as the bolts were secured. This condition was the same for the aluminum post, where the unevenness was too great to permit local deformation of the mounting face. The patterns indicated that severe buckling of the bottom back flanges would take place.

In the 90-deg position of loading it was interesting to note that no patterns were observed on the theoretical tension member. This means that this member is lowly stressed compared to the bolting areas.

STRAIN GAGE TEST

SR-4 strain gages were used to measure strains in each guardrail post tested, and a general calibration survey was made on the tension member of the 2-rail H-beam post, one aluminum and one steel. Figure 3 shows a typical strain gage survey.

When using strain gages in conjunction with brittle lacquer highly accurate strain measurements can be made. The gages were oriented at right angles to the cracks in the brittle lacquer. If this were not done, small changes in direction and location could cause serious errors in strain measurements.

A load of 2,580 lb was selected for strain gage testing to stay safely within the yield strength of all castings tested. It is impossible in this paper to report all strain gage data obtained, but the following values are representative for the highest critical

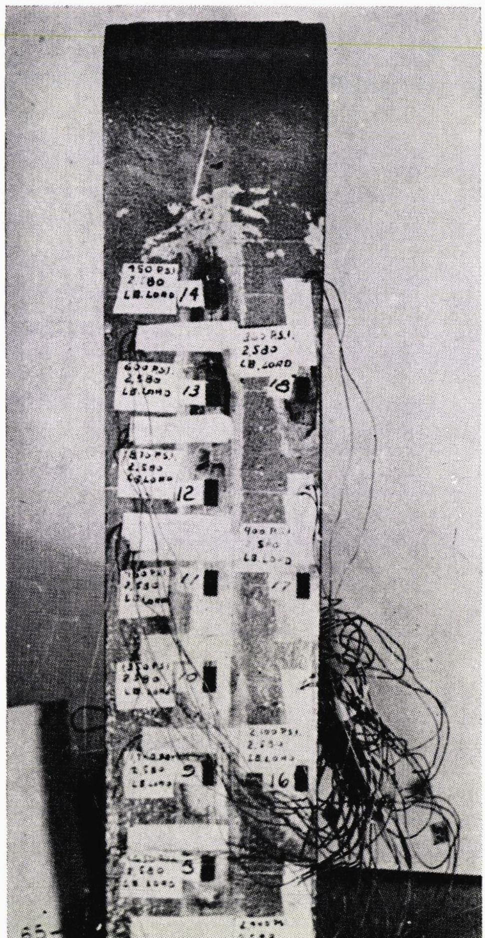


Figure 3. Typical general strain gage survey on tension member of rail post.

stress point in the fillet junction of the front flange to the bolting plate: For the 2-rail aluminum casting of the H-section at a 20-deg load the stress in the fillet was 15,000 psi. For the 2-rail steel casting of the same design and loading the stress in the identical location was 24,600 psi. The modulus of elasticity for aluminum is 10,300,000 lb, and the modulus of steel is 30,000,000 lb. The tensile strength of the aluminum was 35,000 psi; of the steel, 75,000 psi. The elongation of the aluminum was 6 percent; of the steel, 30 percent.

The two designs are nearly equal in yield strength but the difference, which lies in the tensile strength and elongation, will be shown later.

The strain gage data showed the stresses were much lower on the tension face than on the bolting areas; therefore, the design was not compatible with the bolting arrangement. Certainly the upper portion of the posts tested are over-designed, indicating that some of the metal could be used in the critically high stressed fillet of the bolting flange.

DESTRUCTION TESTS

Two points must be discussed with respect to the destruction test. First, it is difficult to predict the actual load for a static failure from strain gage data due to the fact that a great deal of redistribution of strain takes place after the casting passes the yield point. Knowing the yield strength of the material used, the load to cause yielding can be predicted with extreme accuracy. Second, a part almost never is subjected to a static load, as in this case if the load applied to a guardrail is considered as a sudden load, the load to cause the same deflection and stress would be only one-half that of a static load. Also, the ability of a part to withstand this load is inversely proportionate to the square root of the modulus of elasticity. Therefore, the static failure test cannot be conclusive information without knowledge of the exact type and magnitude of load which causes the failure. However, once the dynamic conditions of the loading have been established, the static failure test can be correlated conclusively.

Therefore, the destruction tests are for the purpose of visually depicting the failure points and load to cause failure statically. One aluminum, one regular steel and one alloy steel post of similar H-section 2-rail design were tested to destruction.

Aluminum 2-Rail, Load Applied at 20 Degrees.—The strain gage in the critical fillet of the aluminum 2-rail post with load applied at 20 deg was monitored and at 5,000-lb load the stress was 22,300 psi. This was the yield point. The casting broke at 14,200-lb load with rupture starting in the critically stressed fillet. Figure 4 shows the results of the destruction test of the aluminum casting. Failure is through the strain gage axis.

Regular Grade B Steel 2-Rail, Load Applied at 20 Degrees.—Once again at 5,000-lb load the stress nearly reached the yield of 41,200 psi. The front bolt failed at 22,000-lb load. However, the steel casting had undergone considerable deformation and a small rupture crack was observed in the fillet junction of the bottom bolt plate and center web (Fig. 5).

AISI 8635 Steel Alloy Heat-Treated to 241 BHN, Load Applied at 20 Degrees.—The casting yielded at 9,000-lb load and a stress of 96,750 psi was recorded. This was the yield strength of the material. The bolt failed at 26,000-lb load (Fig. 6). There was a very limited amount of deformation observed in the alloy casting and no cracks were visible.

Figure 4. Static failure of aluminum post at 14,200-lb load.

OBSERVATIONS DURING DESTRUCTION TEST

Strains recorded during the destruction test for the three materials used have been plotted in Figure 7, from which the significant difference in strength between the aluminum and steel materials becomes quite obvious. First, the test bar data beyond the yield strength must be disposed of, as this information is of no value to the designer or analyst under these circumstances. The post, when subjected to loads that cause failure, did not exhibit the test bar specimen results after the post passed into the plastic range. Also, because the loads were applied in increments, considerable work hardening of the fillet took place. This is quite common in a highly critical stress riser when the yield point of the material is exceeded. The plots also exhibit true stress-strain curves. The curve for the aluminum has a very flat slope after it passes into the plastic range. Even though the fillet has recoverable strain at each load increment, the flatness of the slope allows a great gain in strain with a very small increment of loading.

The steel castings exhibited a very steep slope, which allows the load to increase sharply for a small increase in strain. This property has been found in steel castings during other tests. This fact applies only to static loads or a limited number of cyclic loads or non-fatigue circumstances.

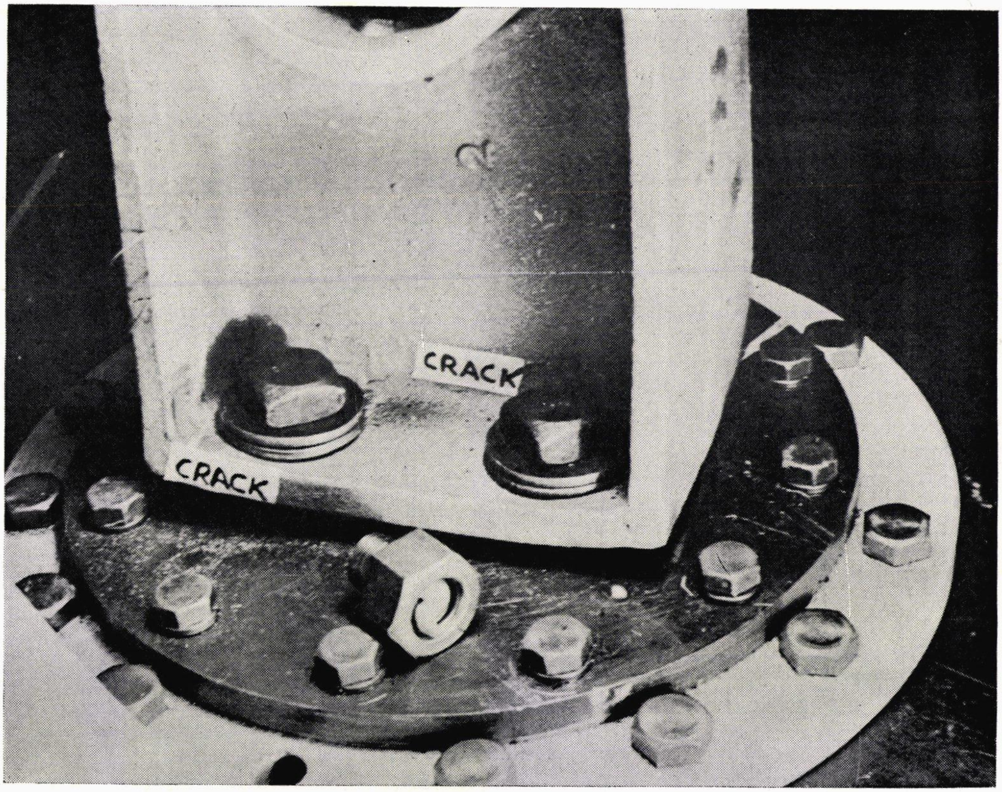


Figure 5. Static failure of front bolt at 22,000-lb load, regular Grade B steel post.

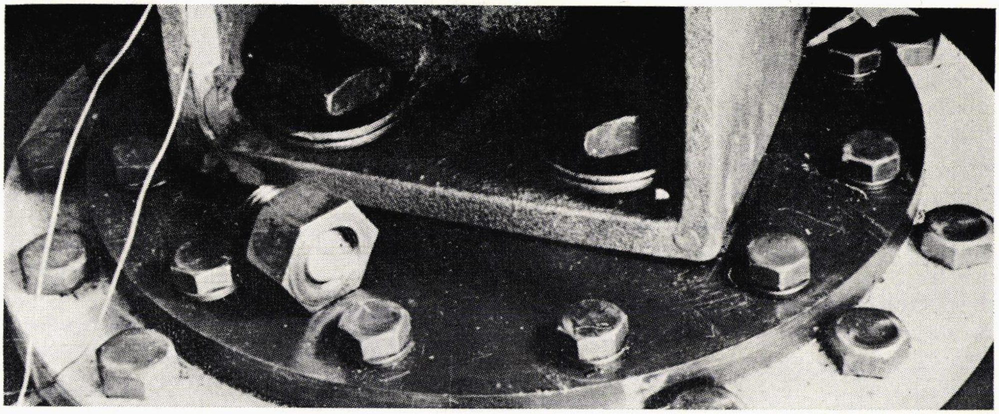


Figure 6. Static failure of front bolt at 26,000-lb load, AISI 8635 steel alloy post.

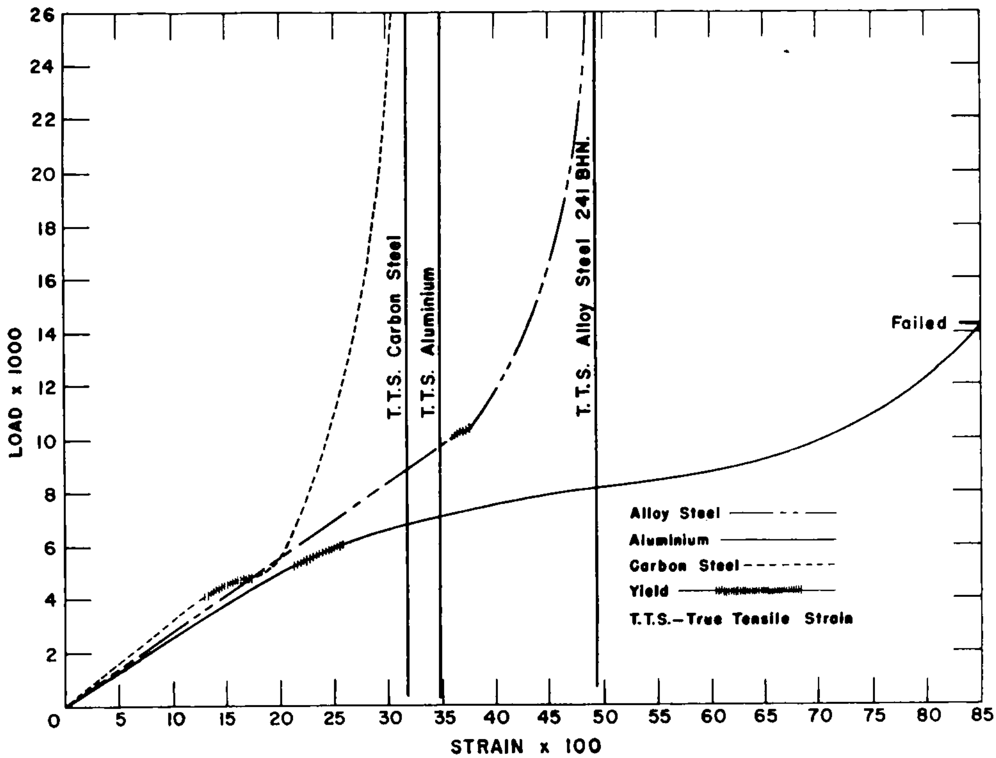


Figure 7. Comparison of strains recorded during destruction test.

The foregoing findings point out the importance of experimental stress analysis for analyzing design rather than applying theory and using mere test bar data.

Modified H-Section Design

From this design and materials correlation it can be concluded that a steel casting is well suited for use in a bridge guardrail post system. Furthermore, it was obvious from the experimental stress analysis data that a slight design modification in the highly stressed fillet area of the H-section design post would bring about a balance between the present bolting arrangement and a regular carbon cast steel post. Therefore, a program was set up to develop the design modification and run tests. This was an immediate action that could strengthen existing posts being used on new construction or as replacements without altering the present bolting arrangement or affecting appearance drastically.

The design modification shown in Figure 8 consisted of moving the front flange forward 1 in., thereby allowing for a larger fillet without altering the bolting arrangement. The front boss on the load side was increased to 1¼ in. in thickness, thereby putting metal right where it is needed, the larger fillet reducing the high critical stress riser.

Stresscoat patterns showed an improvement in the fillet, also other areas of the side to which the 20-deg load is applied. The strain gage survey showed a 68.5 percent reduction

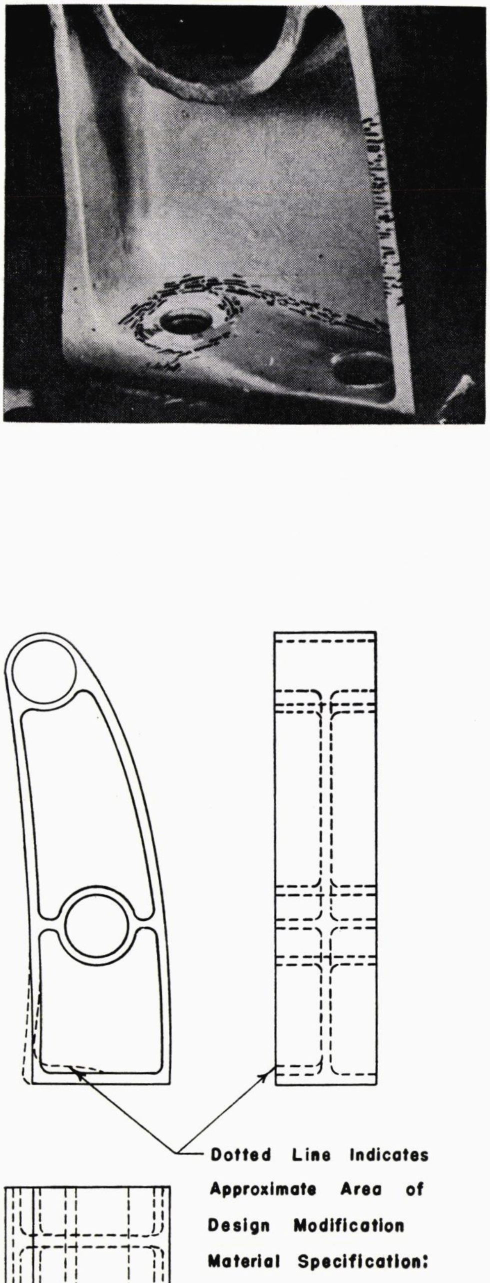


Figure 8. Brittle lacquer patterns showing improvement in the fillet junction of the modified H-section design.

in stress in the fillet area. In destruction tests at 23,800-lb load both 1-in. bolts broke at the same instant (Fig. 9). This is quite significant, because in the original destruction test only the front bolt broke at 22,000-lb load.

The modified design casting was stable to the 9,000-lb load, as compared to yielding at 5,000-lb load of the original design. The goal of modifying the present design without altering the bolting arrangement or affecting appearance drastically has been accomplished. This is shown by the fact that the two bolts failed without cracking the casting, as was the case in the previous destruction test. Little more can be done to increase the efficiency without changing the bolting design, inasmuch as both bolts are now being utilized.

OBSERVATIONS

During the course of testing a number of observations were made, from which definite conclusions are drawn

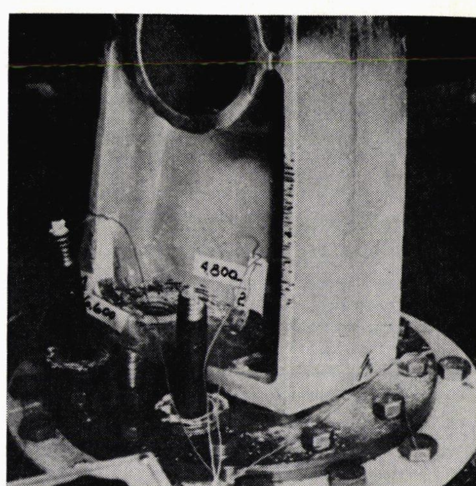


Figure 9. Static failure of the two bolts at 23,800-lb load, regular Grade B modified H-section design.

later in this report. These observations are as follows:

1. The body of the casting was not compatible with the bolting flanges: that is, with the exception of the channel section design, nearly all stresscoat patterns were observed in the junctions of the body of the casting to the bolting flanges or directly on the flange itself. The destruction test proved this when the aluminum casting broke directly through the junctions of the casting and through the axis of the strain gage. The two steel castings had extreme deformation of the bolting flange. Rupture cracks were visible in the body junctions of the annealed regular steel casting.

2. Regular bolting arrangement does not appear to be adequate. One-inch commercial bolts were used in the destruction test. These can be considered as a minimum strength level for this purpose. The ductility and strength level of steel bolts are important factors in achieving a satisfactory anchorage. Even during the test in which the aluminum casting failed, the bolts were severely elongated. This casting had failed below the 18,000-lb static load which is considered adequate for some rail systems. However, upon further study and analysis of actual conditions, opinions have been expressed that the static load should range from 50,000 to 100,000 lb. The bolts on the steel castings failed before breaking the casting. Therefore, the strength of this attachment must be evaluated because it would be foolish to search out a new design only to have the bolts be a limiting factor.

3. H-beam design is not suited for a 20-deg load. As was pointed out previously, the H- or I-beam design is not compatible with torsional loading. The stress differential between 20-deg loading and 90-deg loading was as great as 200 to 300 percent higher in the 20-deg position; yet 20 deg is the angle which has been established as that at which the car strikes the rail. For the post to be struck at 90 deg is a virtual impossibility.

4. Alloy material adds strength to the post but is not a definite solution to the problem. Doubling the strength of the material does add strength to the post, but loss of ductility could be detrimental when shock loads are considered. This is especially true with the number of stress risers existing on the present design; yet, alloy would be fully utilized if this part were uniformly stressed. Cost would also have to be a consideration when determining the feasibility of using alloy materials.

5. The weight of the steel castings tested is excessive. The steel casting when compared to an aluminum casting of the same design is much too heavy. This could be overcome through improved design, ridding the post of much of its unused metal. This seemed to be especially true of the 3-rail post castings, which weighed 182 lb each. This weight factor could present serious problems during installation and handling.

6. The elongation of the material is in favor of steel casting. At the point of failure in the fillet which was a critical stress riser, both the aluminum casting and the regular steel casting yielded at approximately the same load during the destruction test, yet the aluminum casting broke at 14,200-lb load and the steel casting was still bending at 22,000-lb load when the bolt failed. Much of this can be traced to the fact that the aluminum casting had an elongation of only 6½ percent, whereas the steel casting had an elongation of 31.2 percent. This difference has two effects. First, the greater ductility allows more redistribution as the part deforms. This is especially

true when the stress becomes distributed over a part of great length. Second, the tensile strength of the material is raised to the true tensile strength proportionate to the elongation.

7. A number of defects were found in the steel castings tested. These defects ranged from external shrinkage cavities to hairline cracks. The defects will have little or no effect on the static strength of the post as long as they do not occur directly in one of the critical stress risers.

CONCLUSIONS

As tested, steel castings of present designs have exhibited superior strength. Steel's ability is basically due to its greater elongation, which allows it to absorb a greater amount of energy or load before failing. This added strength lends itself ideally to the deceleration problem involved in the guardrail situation. The foregoing factor is directly related to the design shape and must certainly be considered in future post development. To realize the full strength of cast steel, the post design shape must permit as uniform stress distribution as possible; in short, it must eliminate stress concentration points. This would result in greater utilization of the higher strength properties of cast steel.

Obviously, the anchoring of the cast post tested must be improved. The method of improving the mounting will have a direct bearing on the design shape in the critical base area to resist the leverage moment. The beam strength of the post can be increased but cannot be fully utilized without some type of improved anchorage.

The upper portion of the post is relatively low stressed, therefore over-designed. The relatively uniform H-section throughout the length of the post is an inefficient use of material. It would be better to increase the base mounting section, allowing more taper toward the top of the post. It would be difficult, if not impractical, to gain a major strength improvement by making only further minor design modification in the types of posts tested to date.

Sound metal free of defects is essential in the critical base area. This point indicates that it is necessary to establish practical inspection procedures if these designs are to be used.

Further investigation of actual loads must be made and correlated to the static load. This will allow more efficient designs to be developed as future designs can be better tested statically by experimental stress analysis prior to testing under actual conditions.

The results and data obtained by this method of development indicate that it is feasible to develop a fail-safe bridge guardrail post system utilizing a cast steel post as the critical backbone of the system.

The basic design shape of the post can be developed so as to be adaptable to most box, tubular, or corrugated ribbon rails. The design shape can be developed to accommodate an improved anchorage system and eliminate all stress risers to achieve a uniformly stressed post.

Encouraged by successful completion of phase one, the Society has approved funds for phase two, which has as its goal the development of a basic post design shape for the optimum bridge guardrail post system.

One other conclusion can be drawn from this program to date. This engineering method is well suited to evaluate other bridge components, such as shoes, rockers, and counterweight sheaves for design development as high-strength lightweight steel castings.

By reporting phase one of the program, it is hoped to establish a sound engineering procedure for further progress and cooperation to bring about a successful solution to the guardrail post systems problem, plus utilizing this basic method or engineering approach to other bridge design problems to more fully use the potential of steel castings.