Radiographic Inspection of Welded Highway Bridges

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Procedures and standards for radiographic inspection as applied to welded structural steel highway bridges have not been clearly covered by any nationally-accepted specification. This paper outlines the procedure and standards followed by the California Division of Highways and develops data to indicate the necessity for uniform standards covering practical application to highway bridges. Limited recommended standards are included.

• DURING the past ten years, the California Division of Highways has constructed 242 bridges containing 110,000 tons of welded structural steel; at present it has 56 bridges under contract which will require 42,000 tons of welded structural steel.

Radiography has been used as the primary nondestructive method of examining the major stress-carrying butt welds of all of these structures. Its use, both as a working tool to locate and correct defects, and as a factor to insure the integrity of welded structures, has been successful. The cost of such radiographic work is nominal when the usefulness of the radiographs is considered. However, a problem arises in the use of radiography because of the lack of universally-accepted standards developed specifically for application to highway bridges. The purpose of this paper is to show the need for such standards and to offer a suggested approach to the problem.

The current edition of the American Welding Society's "Specifications for Highway and Railway Bridges" (modified to a slight degree) is used to control the welded structural steel fabrication of the California Division of Highways. In accordance with these specifications the contractor is informed when radiographic inspection is to be performed and of the radiographic standards to be attained. The cost of the radiographic inspection is borne directly by the state.

Because different types of bridge structures provide a variety of welded joints needing radiographic examination, it is difficult to quote a meaningful cost for such work based on tonnage of fabricated steel. A more realistic figure is the cost for each reported 4.5- by 17-in. radiographic plate. This is the standard size film used by California for bridge work. Presently, this radiographic work costs an average of $5.50 per film, whereas in 1955 the cost was about $7.50 and in 1949 about $25.

This cost per radiographic picture varies from $2 per film to as high as $7 per film, depending on the thickness of joint, source of radiation, and ratio of travel time to radiographic time. These factors are influenced by the size and design of each project and whether or not the radiographic work is done for shop fabrication or field erection.

In California the actual radiography is performed in the shops by commercial laboratories under service agreement and in the field by state personnel equipped with the traveling unit shown in Figure 1. California has standardized on the 4.5- by 17-in. radiographic plate.

The question is often raised as to whether or not the requirement that the work will be subject to radiographic inspection has an effect on the contract bid price of welded structural steel, even though the actual cost of the radiographic inspection is not a part of the contract. California analyzes bid prices on a quarterly basis. Based on this anal-

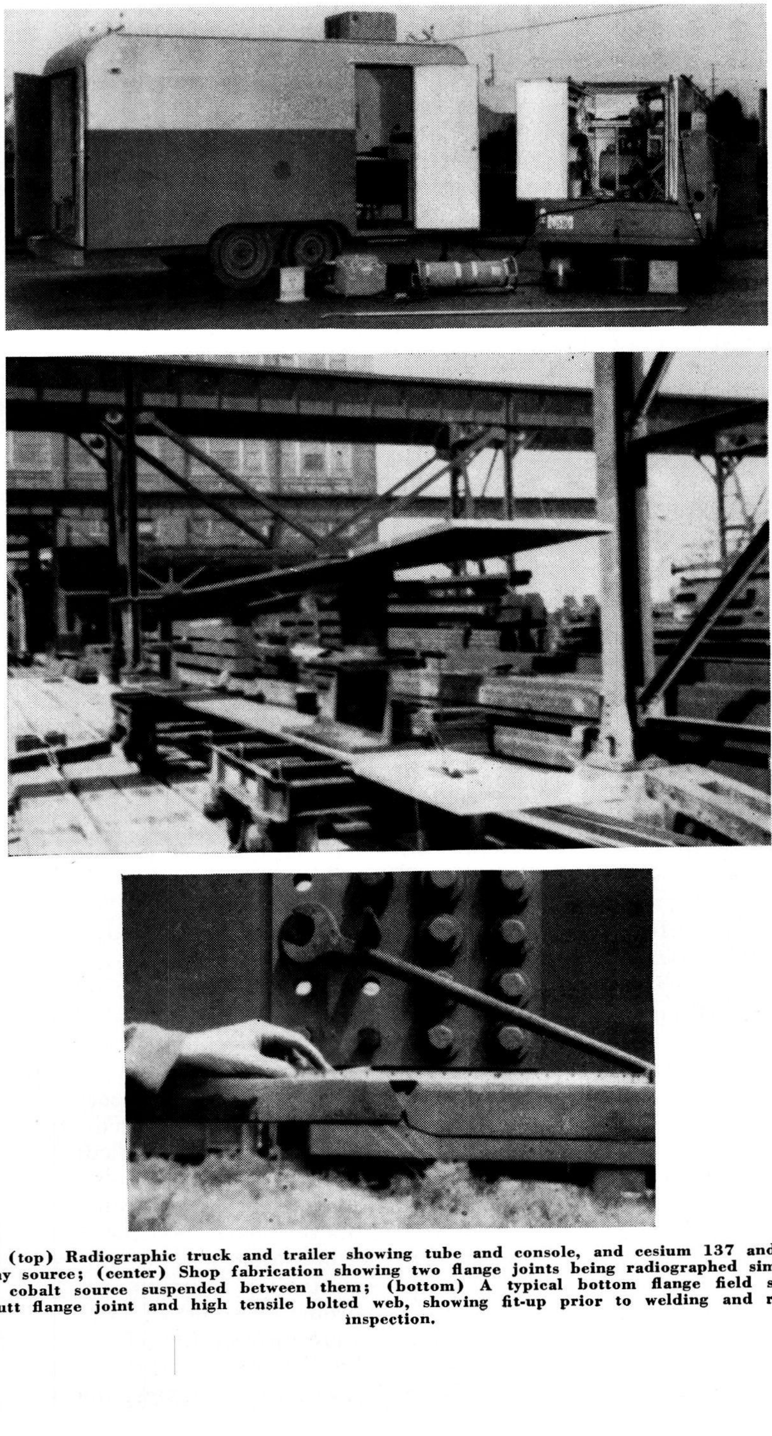


Figure 1. (top) Radiographic truck and trailer showing tube and console, and cesium 137 and cobalt 60 gamma ray source; (center) Shop fabrication showing two flange joints being radiographed simultaneously by using cobalt source suspended between them; (bottom) A typical bottom flange field splice using welded butt flange joint and high tensile bolted web, showing fit-up prior to welding and radiographic inspection.

ysis and general observation of comparable efficiencies in the shops before and after being subject to the discipline of radiography, it is considered that there is little effect. The most noticeable effect is that the general competence of the welders increases, which results in better quality work and a decrease in corrective repair work required.

INSPECTION PROCEDURE

With the possible exception of two steps, the fabrication inspection procedure followed by the California Division of Highways is approximately the same as that in general use throughout the United States. The two steps which may represent differences are (a) a prefabrication conference, and (b) the procedure used for radiographic inspection.

The California fabrication inspection procedure for welded steel bridges can be divided into five important steps, as follows:

1. Prefabrication conference, at which the methods and procedures to be followed by the fabricator and by the inspector during fabrication are discussed informally. The important details and requirements of the plans and specifications are thoroughly reviewed at this time and any differences of opinion are resolved in advance of the actual start of fabrication. This discussion is usually scheduled just before the shop drawings are submitted for approval.

2. Prequalification of manual welders, automatic welding machine operators, and welding procedures. The first use of radiography is made during this period in that each butt welded qualification plate is radiographed before the mechanical tests are conducted. This not only shows what is meant by "radiographic quality," but also eliminates useless machining and testing of defective plates.

3. Identification of the steel to mill test reports by the inspector. Mill test reports are witnessed and verified by a representative of the state at the mill. Under specifications only a small amount of unidentified steel may be furnished, such steel is sampled and tested by state personnel. During this time special emphasis is placed on a means of positive identification of special steels as they are cut for use throughout fabrication.

4. Continuous visual inspection, supplemented by nondestructive testing as necessary during actual fabrication. Penetrant dye, hardness testing, and radiography are the primary types of nondestructive tests used during actual fabrication. Approximately 80 percent (this may be increased or decreased, depending on job experience) of all butt welds to be used in primary tension are radiographed, and a spot radiographic check of all such welds to be worked in compression is also performed (the amount depends on job experience). Radiography is not used on fillet welds. Butt welding is controlled by visual inspection supplemented by radiography, whereas fillet welding is controlled by visual inspection supplemented by the use of penetrant dye.

5. Final inspection before and after sandblasting, supplemented by an inspection after shipping to the site, for possible shipping damage. This latter inspection is performed by the construction engineer, who will also include an "after sandblasting" inspection if sandblasting is to be done in the field.

NEED FOR RADIOGRAPHIC BRIDGE STANDARDS

A random analysis of 5,808 radiographic plates exposed during the fabrication inspection of California bridge structures shows that 7 percent of the welded butt joints were not acceptable. These defective joints occurred in spite of competent visual inspection and prequalification of both procedure and personnel, as well as full knowledge by the welder that the weld was subject to radiographic inspection. It is considered that this figure would have been higher had the fabrication not been subjected to the discipline of radiography. It is true that probably some of the defective welds were already known by the inspector to be defective and that advantage was taken of the nonargumentative position an inspector assumes when backed by a radiograph. This, however, does not affect the fact that 7 percent of the welded joints designed to carry major tensile stress when first fabricated did contain serious defects.

At present Paragraph 707 of the 1956 Standard Specifications for Welded Highway and Railway Bridges of the American Welding Society (*4*) states that the radiographic procedure technique and standards of acceptance shall be specified or shall conform to commercial practice. It is then stated as a footnote that the ASME Boiler Code, Section VIII, Paragraph UW-51, is an example of such practice. This code is one of the few generally-accepted commercial specifications in existence and is excellent for the purpose intended.

It should be noted that the 1956 AWS Bridge Specification (*4*) does not contain an internal weld quality standard for inclusions, as did the 1947 edition. This omission was well considered by the 1956 AWS committee, which felt that insufficient information was available at that time to arrive at a definite bridge standard and that it would be better to include no information rather than something that would be subject to immediate revision.

However, the joints of a highway bridge structure and of a pressure vessel are subjected to different types of loading, and although the standards for allowable defects in a welded joint of a pressure vessel are somewhat acceptable for a highway structure, there are several factors that need modification.

The first is porosity. Whereas in a pressure vessel porosity requires separate consideration, in a bridge structure it is merely another defect and need be treated no differently than the inclusion of slag or other deleterious material. It is recognized that the uniform sides of a gas bubble are probably less likely to act as stress raisers than are the sharp edges of the hole caused by a piece of slag; however, at present it is not felt that sufficient information is available to justify the additional interpretation that would be made necessary by segregation of the two. The major difference between the welded joints of a pressure vessel and those of a bridge is that the pressure vessel joint normally has no free edges, whereas a bridge structure joint often has two free edges. The effect of welding defects, as well as the effect of free edges and points of restraint, on the initiation of fatigue and static failures in welded joints has been indicated elsewhere (*1, 2, 3*).

In addition to these points, and of equal importance, is the fact that the ASME code does not lend itself readily to the required speed of quantitative analysis for bridge work.

It will be noted that this discussion is primarily concerned with allowable inclusions, while other defects have been ignored. As indicated in the suggested standard (Fig. 2), it is considered that cracks, lack of penetration, overlap, and incomplete fusion cannot be allowed. This is in accordance with both the AWS and ASME codes, and no change is suggested or considered desirable.

CALIFORNIA RADIOGRAPHIC PROCEDURE

The purpose of radiography in the welding inspection process is to show the presence and nature of defects in the interior of welds. This can be done, but to do it properly it is necessary to clearly define by a specification both the procedure and method of radiography to be used and also to define the acceptable size and distribution of such defects in a welded joint.

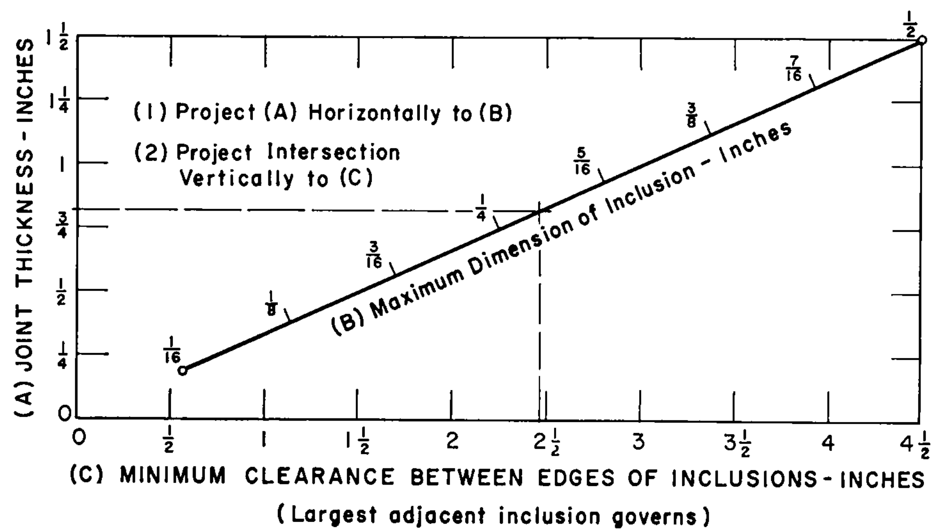
California follows the procedures outlined in Paragraph UW-51, Section 8, ASME "Boiler and Pressure Vessel Code" (*5*), insofar as radiographic technique is concerned. California specifications further outline that lack of penetration, incomplete fusion, or cracks of any type are unacceptable. In addition, the presence of slag, porosity, or other inclusions in excess of the limits specified in Paragraph 607 of AWS Specification D2.0-47 constitute cause for the rejection of such welds as defective.

PROPOSED CALIFORNIA RADIOGRAPHIC STANDARD

All butt welds designed to carry primary stresses shall be subject to radiographic inspection. The presence of any of the following listed defects in excess of the limits indicated shall result in rejection of the weld as defective:

1. Cracks — no cracking shall be allowed regardless of length or location.
2. Overlaps, lack of penetration, incomplete fusion — none shall be allowed.
3. Inclusions; including slag, porosity, and other deleterious material, — less than $\frac{1}{16}''$ in greatest dimension shall be allowed if well dispersed such that the sum of the greatest dimensions of the inclusions in any linear inch of welded joint shall not exceed $\frac{3}{8}''$ and there shall be no inclusion within $1''$ of the edge of a joint or a point of restraint.
4. Inclusions; including slag, porosity, and other deleterious material, — $\frac{1}{16}''$ or larger in greatest dimension shall be allowed providing such defects do not exceed the limits indicated by the accompanying chart.

SUGGESTED STANDARDS FOR ALLOWABLE INCLUSIONS



NOTE:

1. Minimum distance from edge of inclusion to free edge of plate or toe of flange fillet weld is twice the clearance between inclusions.
2. Inclusions with any dimension greater than 1/2" are not acceptable.
3. For joint thicknesses greater than 1-1/2", the minimum allowable dimension and spacing of inclusions shall be the same as for 1-1/2" joints.

Figure 2.

There is no question but that any primary structural weld should not contain any of the first-mentioned defects.

The second part of the specification, however, needs revision because it could be unduly restrictive in the case of large defects. In other cases it could be too lenient, such as allowing excessive over-all distribution of small defects or distribution of defects along a free edge or within an area of restraint. Probably one good reason for the unsuitability of this AWS Paragraph 607 in the interpretation of radiographs lies in the fact that it was never intended for such application. Its intent was that it would be applied to macrographic sections cut through the welded joint rather than to a projection of a summation of the defects on a flat plate, such as is done in radiography.

Insofar as highway structures are concerned, the following points are considered to be most important in the technique for radiographic examination.

Radiography of highly stressed tension butt welds should be performed after the joint has been ground. Because all butt welded joints carrying primary tension stresses under California construction specifications must be ground, this does not result in any extra expense insofar as the radiographic procedure is concerned. Butt welded joints that need not be ground for stress carrying purposes may be radiographed in their as-welded condition. This means that the interpreter of the radiograph must be highly skilled so as not to confuse the surface irregularities with internal defects. For training purposes, typical radiographs of past work are used, supplemented by the collections of reference radiographs issued by ASTM (*7*) and by the International Institute of Welding (*8*).

The radiographic technique to be followed must disclose all defects having a thickness equal to and in excess of 2 percent of the thickness of the base metal. To check this, at least two penetrometers must be used. The thickness of the penetrometer cannot be more than 2 percent of the thickness of the plate. The penetrometers are placed at each end of the area to be radiographed. They are both placed on the side of the joint nearest the source of radiation. In addition to this, the film must be carefully identified by the use of lead numbers so that their image will appear on the film but will not interfere with the interpretation of the film. The weld must also be marked by the welder so that he can be held accountable for his work.

In addition to insuring that it will be possible to see the penetrometer, a technique must be followed that will guarantee a sharpness of image delineation. This is of utmost importance in the interpretation of a radiograph, especially if fine cracking is present. This sharpness of the image is determined primarily by the use of the proper source of radiation, film type, and exposure for the thickness of joint being radiographed.

Radiography or any other form of nondestructive testing, while a useful tool to the bridge engineer and inspection, is nevertheless not the cure-all. It cannot be substituted for competent visual inspection, but can only be used to supplement such inspection. It has definite limitations, which must be recognized by all who use it. The possible inability of radiography to detect fine cracks is probably its most serious drawback. Because 2 percent sensitivity is about the maximum that should be expected practically from the radiograph, it can readily be understood how a fine crack in thick material may escape detection. This is one of the reasons why proponents of the use of ultrasonics in the field of nondestructive testing of structural welding are gaining recognition. Unfortunately, the use of ultrasonics in this field presently is limited by the lack of skilled technicians and a lack of education concerning the acceptance and interpretation of the results of ultrasonic measurements.

Radiography is also limited in areas where varying thicknesses of metal must be penetrated, such as the fillet weld used in connecting a web to a flange. Once qualified, this type of weld lends itself better to visual inspection, supplemented by penetrant dye used to disclose the presence and extent of any possible cracking.

PROPOSED RADIOGRAPHIC STANDARDS

In addition to simplification of inspection management, two structural factors have influenced the selection of the suggested standard of maximum inclusion to be used in the interpretation of radiographic film, as shown in Figure 2. These are (a) the indications of restraint in the area directly under a web or other stiffening medium and (b) the indications that a defect close to the edge of a tension stress carrying member tends to concentrate the stress more than if the defect is materially away from the edge of the joint.

Welded bridges are usually designed in accordance with AWS Specification D2.0-56 (*4*), which cites no radiographic standards directly but does refer to the ASME Boiler and Pressure Vessel Code (*5*). Because of this and the lack of quantitative data concerning the effect of weld metal discontinuities on the strength of a welded joint, it is not practicable to detail an engineered system of radiographic inspection which would be commensurate with the intended function of a bridge joint.

Consider the ASME Boiler and Pressure Vessel Code (*5*), for example. Part UW-11 of the code states that all butt welded joints over 1½ in. thick, butt welded joints over 1 in. thick of the harder grades of carbon steel and of low alloy steels, butt welded joints in vessels designed for pressures in excess of 50 psi, and butt welded joints in vessels containing lethal substances should be radiographed throughout the entire length. (Nozzle and valve welds included in this category are not pertinent to this discussion.) Joints other than these need only be spot examined by radiographic methods.

Let it be assumed that a 1⅛-in. welded butt joint is to be employed in such a manner that, in accordance with Part UW-11 of the code, it must be radiographed throughout its entire length. Paragraph M-2 of Part UW-51 states that radiographs of such a joint may show it to contain elongated slag inclusions up to ⅜ in. in length without providing cause for rejection of the weld. Paragraph M-3 specifies that the total length of slag inclusions in any 13½-in. length of the joint must not exceed 1⅛ in. Paragraph M-4 limits the permissible porosity to that illustrated in Figure 2.

The porosity chart of Figure 2 pictures a maximum permissible void size of ⅛ in. at a minimum clear spacing of 4½ in. for a 1⅛-in. joint, and also shows other combinations of pore size and spacing permissible in the hypothetical joint.

However, if the butt joint is to be used in such a manner that only a spot radiographic examination is required, then Paragraph (d) of UW-52 should be used rather than UW-51. UW-52 states that for such inspection a negative may reveal ¾-in. elongated slag inclusions in a 1⅛-in. joint without providing cause for rejection if the total length of slag inclusions in any 6¾-in. of the joint does not exceed 1⅛ in. No maximum limit of permissible porosity is specified in this case.

Both of these standards consider porosity and slag inclusions separately. The question arises as to how one appraises the total effect of such imperfections on the joint when both types occur simultaneously. For application to bridge construction, the validity of segregating and evaluating each type of imperfection separately is questionable because of the inherent lack of precision in qualitative radiographic examination.

Moreover, except for thickness and alloy content, parallels between bridge and pressure vessel design are such that an inspector or design engineer would find it difficult to specify whether the spot or the total method of inspection should be used for a particular joint. Hence, as applied to bridges, the standards in the ASME codes can serve only as arbitrary qualitative requirements necessary to secure the degree of craftsmanship essential in good welding practice.

As previously set forth, the ASME

radiographic standards are qualitative rather than quantitative when applied to bridges. In efforts to circumvent this drawback, many agencies have resorted to Paragraph 607 (d) of AWS Specification D2.0-47 as a radiographic standard for accepting or rejecting welded joints in bridge structures.

This too is somewhat arbitrary, because the number of inclusions or voids permissible in a radiograph of a joint may vary either with the thickness of the joint or with some other interpretation of the inspector. Further, individually acceptable discontinuities may be so oriented as to appear as a single large discontinuity on a radiograph of a joint and thereby cause unnecessary rejection of the weld.

Experience has established that if radiographic standards are to help the shop and field inspector of bridge construction, they must be stated in a concise and explicit manner that will eliminate all uncertainties of interpretation and application.

To accomplish this, the standard shown by Figure 2 has been developed by revising and combining the ASME standards for inclusions and porosity and Paragraph 607 (a) of AWS Specification D2.0-47 in such a way as to fit the requirements of welded bridge construction. This has been done in the following manner:

1. From ASME Code UW-51, the maximum permissible inclusion size ($L=T/3$) for joint thicknesses in ¼-in. increments up to 1½ in., *versus* the minimum permissible spacing ($6L$) assuming optimum (uniformly spaced) intervals between inclusions was graphed as shown in Figure 3.

2. From the same code, the maximum permissible inclusion size ($T/3$) for joint

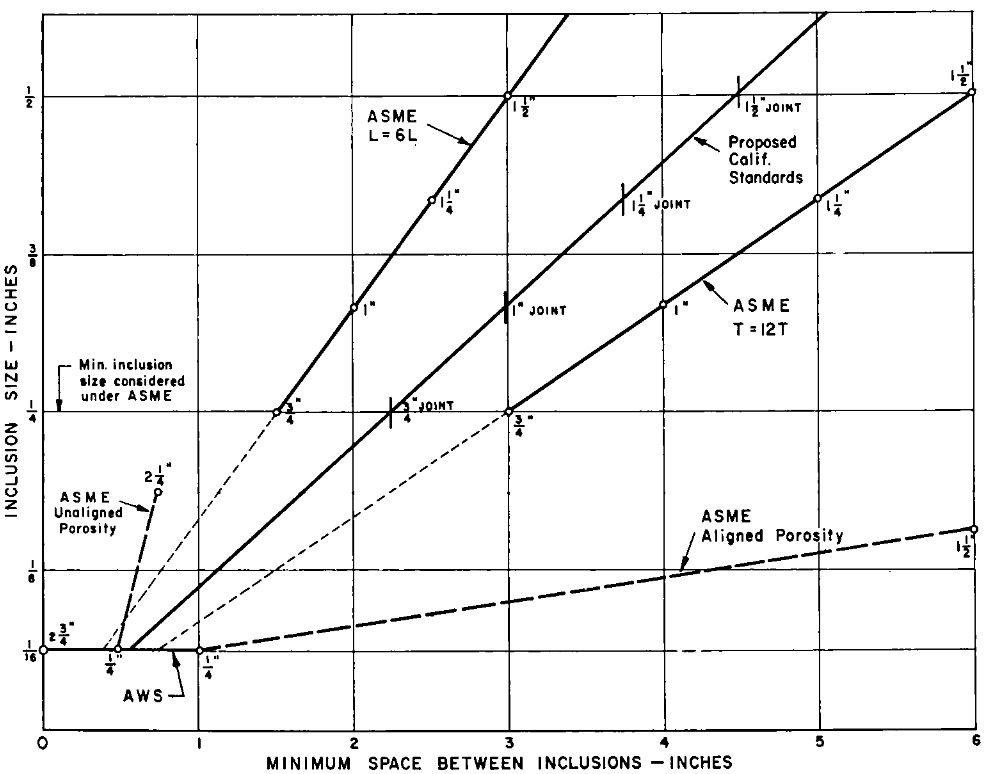


Figure 3. Comparative diagram of inclusions allowed by various specifications.

thickness in ¼-in. increments up to 1½ in. *versus* the minimum permissible averaged spacing assuming non-ideal intervals, was plotted on the same graph.

These limitations are outlined in the ASME Pressure Vessel Code, Part UW-51, Section M, Paragraphs 2 and 3.

3. The variables as taken from Appendix A of the ASME code for porosity and illustrated therein under large unaligned porosity and large aligned porosity were plotted. Here the spacing for unaligned porosity was obtained from the square root of the quotient of the area as measured from the Appendix A illustration divided by the number of voids illustrated. The size of the voids was measured from the illustration.

4. The variables were graphed as they might be interpreted from Paragraph 607 (a) of AWS Specification D2.0-47. In this case it was interpreted that the maximum permissible length of a single discontinuity is 1/16 in. for all joint thicknesses, and the maximum total length of all such in any square inch of weld section is limited to ⅜ in.

The ASME standards on porosity and the interpretation of AWS Specification D2.0-47 set forth in the previous paragraphs were eliminated, inasmuch as extrapolation of the ASME standard for slag inclusions in the same range of inclusion size and spacing overlaps the first two, as can be seen from the graph.

This left the two ASME standards as outlined in the foregoing paragraphs, for spacing of slag inclusion (one based on $L=6L$ and the other on $T=12T$), which were averaged and shown by the line titled "Proposed Calif. Standard," and became the basis for the suggested system of radiographic standard interpretation. This line was replotted (Fig. 2). The allowable size of inclusion was then plotted along this slope and a chart was constructed with the minimum distance between inclusions as the abscissa and with the joint thickness as the ordinate.

At this point an additional limitation to allow for the effect of edge distance and areas of restraint was incorporated. As yet, insufficient data have been accumulated to enable an engineered relationship to be established absolutely between the working stresses of a beam and the position of weld metal imperfections with relation to the sectional and load geometry of that beam. Nevertheless, it is obvious that some arbitrary limits in this direction are advisable.

Nearly all the tests listed by Stallmeyer *et al.* (*3*) indicate the failures to be initiated at a discontinuity in the web adjacent to the tension flange or in the tension flange adjacent to the web. It is felt that this confirms the importance of insuring that the tension flange adjacent to the web be as free of stress-raising discontinuities as possible.

Considering that a point of restraint in the joint (such as the junction of a stiffening member or web) and the free edges of a joint may act as stress raisers in the same magnitude as large concentrations of slag in the weld, they could be considered as a group of irregularly spaced slag inclusions. Section UW-51, M-3 of the ASME code states that the number of such irregularly spaced inclusions must be reduced by ½ over that permissible for regularly spaced inclusions. Therefore, the minimum space between a flange (joint) edge or toe of web fillet weld and an inclusion was set 2 times greater than the minimum distance between interior inclusions. This distance, together with the length of the inclusion involved, and with an allowance for the thickness of the web fillets, determines the minimum flange width that will tolerate the maximum size of inclusion.

The standards set forth in this paper have been applied to a random sampling of project radiographs on file and are found to be practical. They were measured against both ease of interpretation and feasibility under conditions of normal job production as governed by modern welding practice and specifications.

Simulated examples of the application of various radiographic standards are shown in Figures 4, 5, and 6. These examples show the allowable spacing of

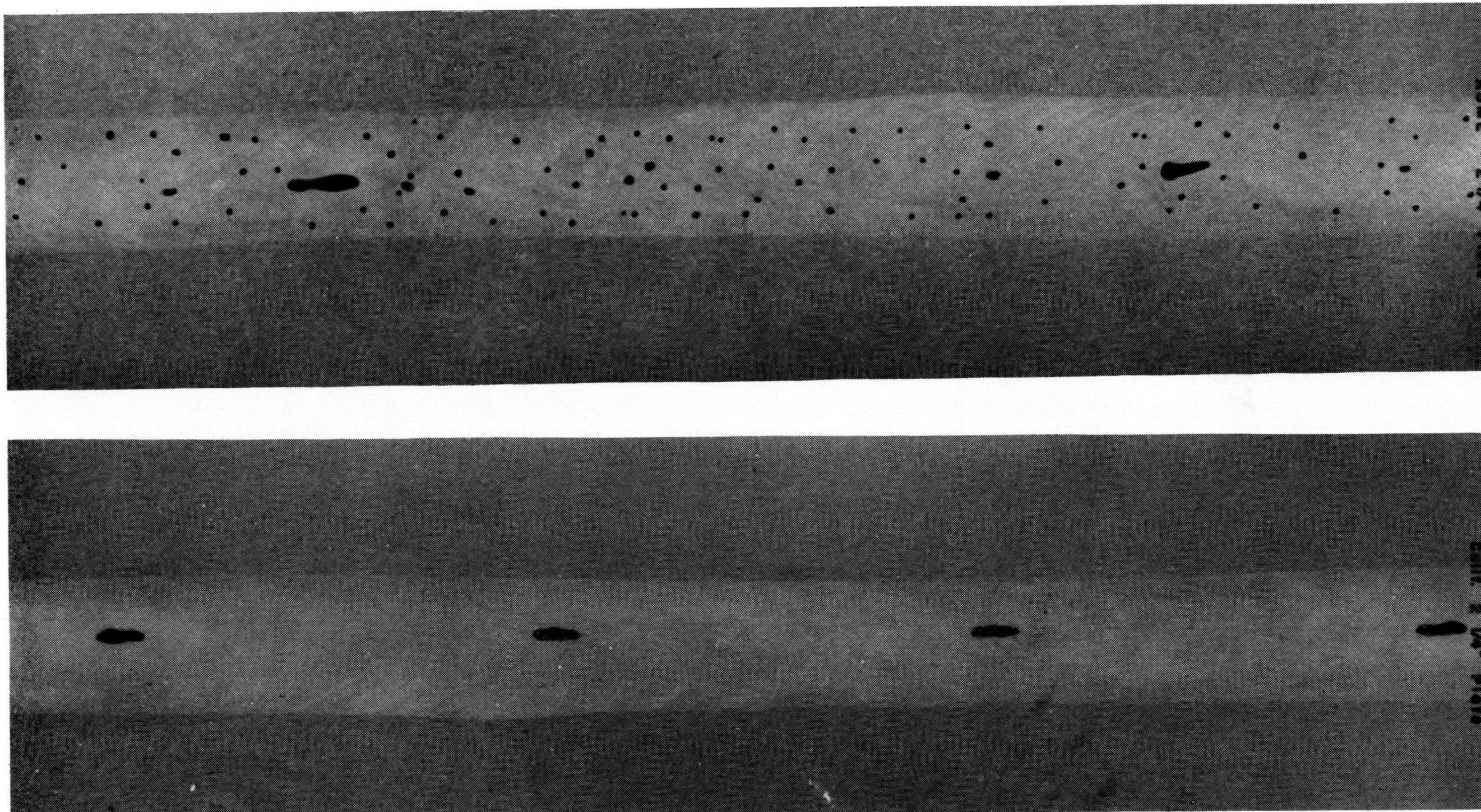


Figure 4. Simulated radiographs (reduced from 4½ by 17 in.) of two maximum conditions that might occur in an acceptable welded joint under ASME Specification UW-51, showing: (top) maximum condition of mixture of porosity and irregularly spaced large inclusions, and (bottom) maximum allowable size and minimum spacing of large regularly spaced inclusions.

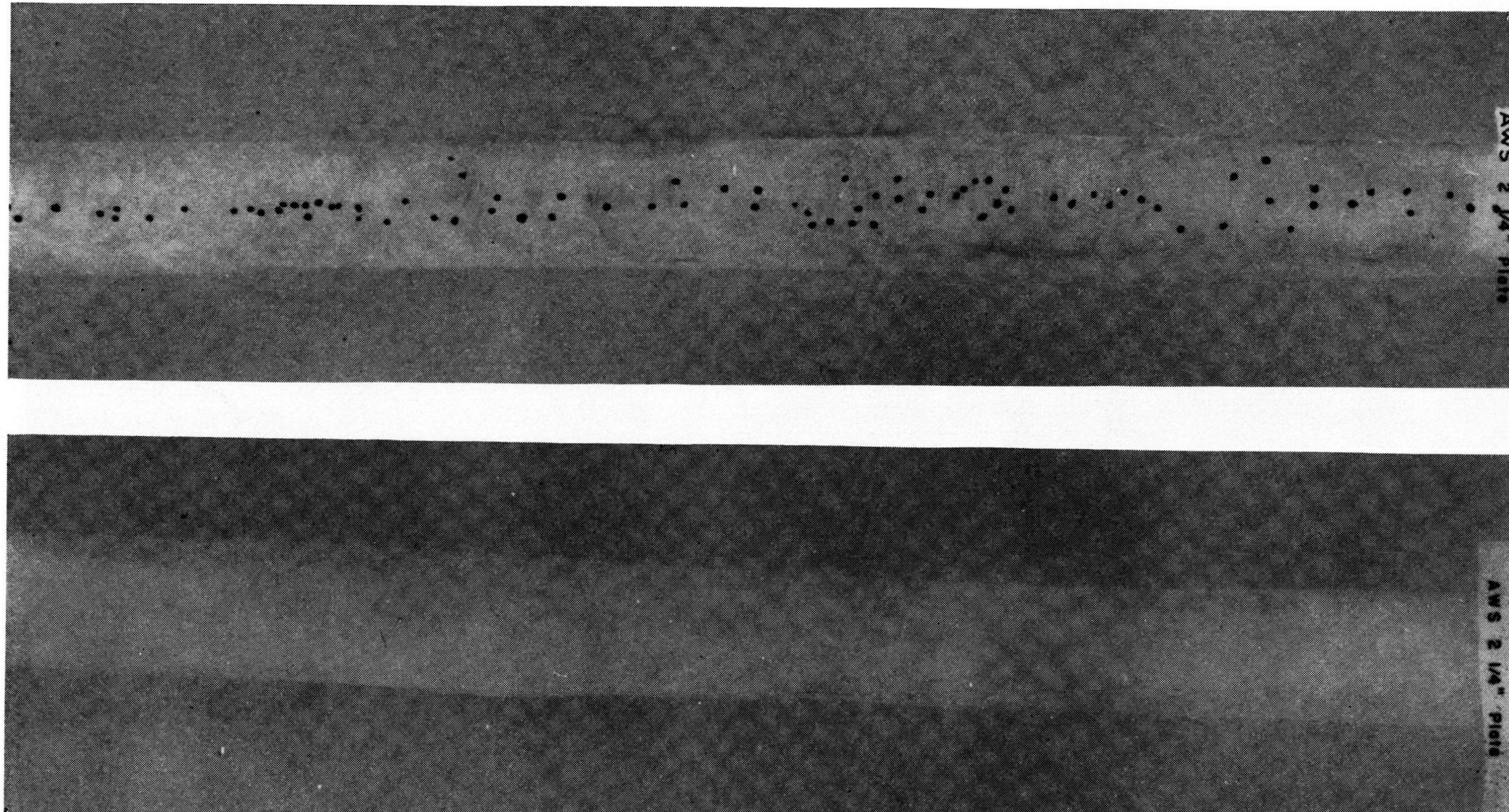


Figure 5. Simulated radiographs (reduced from 4½ by 17 in.) of two maximum conditions that might occur in an acceptable welded joint under an interpretation of AWS D2.0-47 (Art. 607), showing: (top) possible extreme condition of accumulation of 1/16-in. inclusions, and (bottom) condition of joint to be acceptable when considering inclusions larger than 1/16 in.

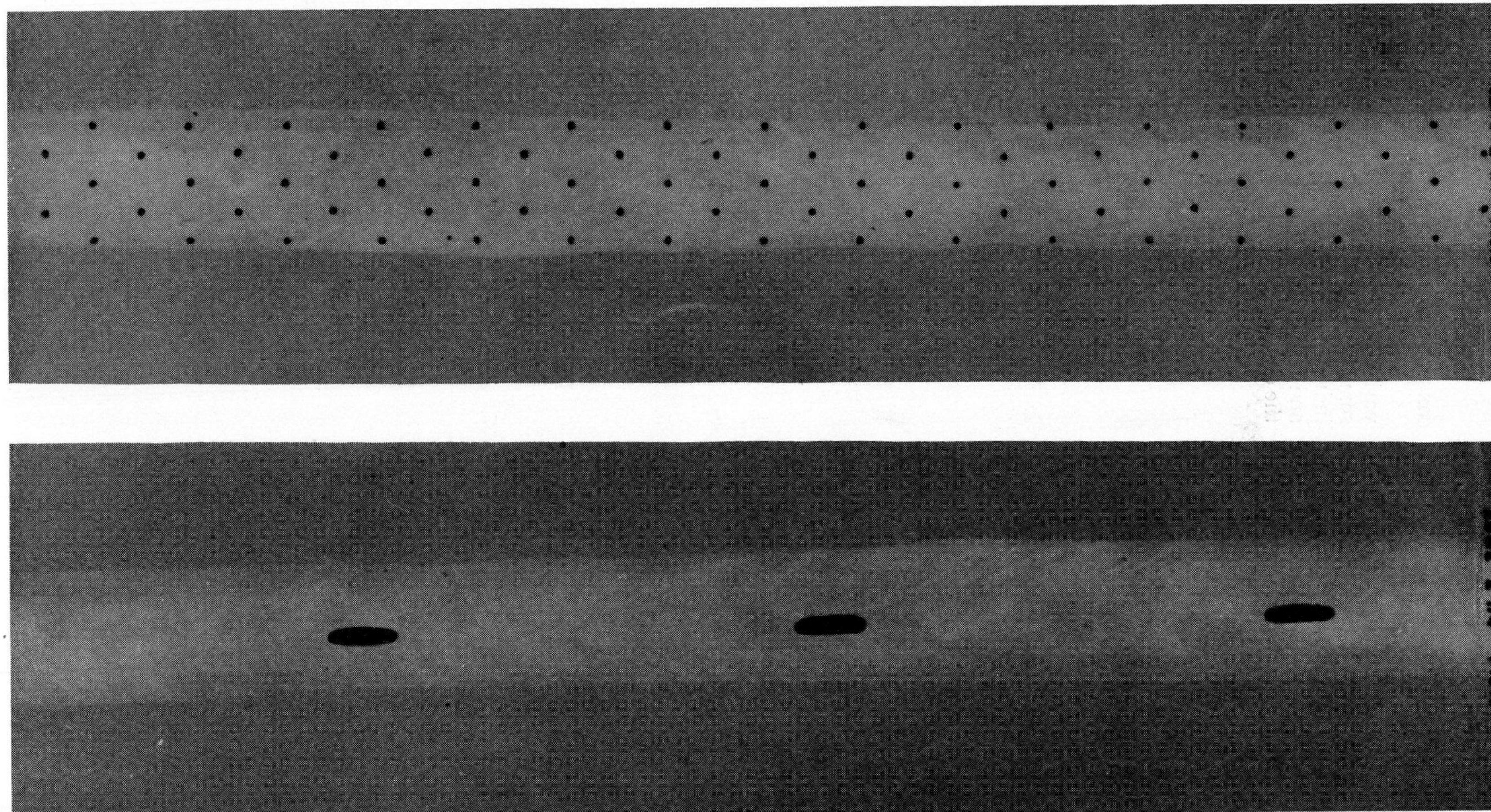


Figure 6. Simulated radiographs (reduced from 4½ by 17 in.) of two maximum conditions that might occur in an acceptable welded joint under the proposed California Radiographic Standards, showing: (top) maximum allowable accumulation of 1/16-in. inclusions, and (bottom) maximum size (½ in.) and minimum spacing of large inclusions.

maximum and minimum sized inclusion under various standards as compared with the standard proposed herein.

SUMMARY

1. The lack of a clear-cut specification for radiography to be applied to welded highway bridges has led to some confusion and misunderstanding as to the value and use of radiography.

2. Radiography, if used intelligently, is well within the limits of acceptable economical inspection charges.

3. Radiography or some other nondestructive means of detection of internal defects is necessary to assure the integrity of a welded structural joint. Radiography is the most practical nondestructive method presently available.

4. Figure 2 presents a suggested standard to be used in interpreting radiographic films of primary stress carrying welded bridge butt joints.

5. Laboratory research is urged to further refine the standards suggested and also to furnish basic data to modify such standards for application to major compression carrying butt welds, web members, and secondary members.

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