SUITABLE STEELS FOR WELDED BRIDGES AND BUILDINGS

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Introduction

Welding is a means of joining metal to metal—nothing more or less.

According to the American Welding Society's "Master Chart of Welding Processes" there are 37 different welding processes used commercially today. For structural fabrication manual shielded metal-arc welding is most commonly used. Oxy-acetylene welding and submerged arc welding are used to a lesser extent; spot welding is used in the fabrication of light-gage structural members.

Structural joints made by welding differ from joints made by other methods in two principal respects:

First: There is a difference in stress distribution, due to the continuous, integral nature of the mass of weld metal across the joint (as distinguished from a row of rivets, for example.)

Second: The heating of the base metal incident to welding has a metallurgical effect on its properties and this effect must be considered and controlled.

Designers of bridges and buildings have been inclined, when using the older joining methods, to disregard the metallurgical properties of steel. They know A7 steel, for example, has certain specified mechanical properties from which safe allowable stresses for different conditions of loading may be established. When it comes to welding, they are impatient with the necessity to better understand which makes a steel behave as it does.

Curiously enough, these same engineers in designing a concrete structure become involved with water-cement ratios, consistencies, setting properties, etc. as a matter of course.

Metallurgical Considerations

The facts which should be known about a steel, in addition to its mechanical properties, for its proper use in welded construction include:

1. Its chemistry, principally the carbon and manganese contents, and the kind and amount of alloying elements present, if any. The usual limits of phosphorus and sulfur are acceptable.
2. How the steel is made, whether it is rimmed, semi-killed or fully killed, and whether it is made to fine-grain practice.
3. The thicknesses of the plates and shapes to be used. Where a joint includes different thicknesses, the greatest thickness is significant.

Let us briefly analyze the meaning of the three factors mentioned.

The chemistry of a steel controls its tensile strength, yield point, ductility and the ratio of these properties to each other. Carbon and, to a lesser extent, manganese, affect these mechanical properties; they are also hardening elements. Alloying elements, when added, may impart strength, hardenability, corrosion resistance, machinability or some other specific property to the steel.

How a steel is made has a bearing on the types of loading to which it may be subjected in a structure. A fully-killed steel, made to fine-grain practice, will, mechanical properties being the same, have the best resistance to impact and dynamic loadings. Its transition temperature (the temperature at which it changes from ductile to brittle fracture) will be lower; hence, it will better resist loadings under severe changes in temperature and will behave better at low temperatures.

The thickness of a steel plate or section will have a bearing on the heat effect of welding. When a weld is made between two pieces of steel, some of the heat flows into the base metal away from the joint. This produces a heat gradient from the edge of the steel at the joint, where the temperature is greatest, to some point away from the joint, where the steel base metal is at the ambient temperature. The heating and subsequent cooling thus produced during welding alters, to some extent, the metallurgical properties of the portion of steel which has gone through this cycle. The distance to which this heat effect extends into the base metal back away from the joint defines what is known as the "heat-affected zone."

When a thick piece of steel is heated during welding, this heat-affected zone is narrower than for a thin section. That is, a given heat input is absorbed by the larger mass of the thick section in a shorter distance from the point of welding than it is in the lesser mass of a thin section. A narrow heat-affected zone provides a less gradual transition in the metallurgical structure of the metal. Among other things, this results in a tendency toward greater hardening and higher shrinkage deformations.

There are ways of either offsetting or reducing this condition. At this point, it is only necessary to note the factors which may have a metallurgical effect on steel and briefly consider why and how. You will remember that these factors are: chemistry, mill practices, and geometry or thicknesses of members to be joined.

Fortunately, most of the steels used for bridges and building construction are readily welded, with a minimum of metallurgical effect on their strength-carrying properties.

Because the practical aspects of the above considerations are different for bridges and buildings, it is desirable to separate these two types of structures and discuss them separately.

Let Us First Consider Steel for Buildings

The "Standard Code for Arc and Gas Welding in Building Construction" of the American Welding Society forms the basis for welding requirements in practically every city of significant size in the United States. Article 106 of this code provides for the use of steel conforming to ASTM Specifications A7. This is the old standby for building construction, based on mechanical properties alone except for limitations on sulfur and phosphorus. This code further provides, in article 403(h), "When welds are being made in parts where thicknesses of more than 1½ inches are involved, the base metal adjacent to the welding shall in no case be at a temperature of less than 70°F."

Provision for the use of A7 steel is based on its general suitability for buildings or other structures subjected essentially to static loading. The additional requirement for preheat is intended to take care of the thickness effect mentioned earlier, plus the fact that the carbon and manganese contents of A7 steel increase with increasing thickness.

Practically all of the welded buildings erected during the past 25 years have been made of A7 steel, and no difficulty has been encountered in service. While the 1½ inch thickness limitations probably takes care of 90% of the construction, some of the sections have been 2 and 2½ inches thick and more.

Currently, the AWS Committee on Building Codes is reviewing the base metal requirements of the code. There are 2 schools of thought to be reconciled: One advocates the use of a steel, other than A7, with a specified chemistry when thicknesses of over 1 or 1½ inches are involved. The other, favors the exclusive use of A7 steel with special, specific workmanship requirements enforced for thicknesses over 1 or 1½ inches. Both approaches are valid, and arrive at the same result. From a practical standpoint the question is resolved on the basis of whether it is more economical to pay an extra charge for a steel, or to spend an additional cost for special workmanship requirements. This is something to be worked out by the fabricator and engineer for their particular conditions.

Pending the adoption of revised provisions in the AWS Building Code here are my own recommendations (for which I shall probably be criticized by advocates of both schools.)

1. Use A7 steel for plates and shapes in all thicknesses up to and including 1½ inches.

   A mill report should be obtained for each heat of steel. Where this report shows carbon plus 1/6 manganese to be over 0.43% ladle analysis, (equal to about 0.31 C and 0.75 Mn), particularly in thicknesses over 1 inch, some special requirement should be imposed as recommended for thicker sections later.

2. Use A7 steel for plates and shapes in thicknesses over 1 inch up to and including 2 inches. If the mill report shows the carbon equivalent to be in excess of 0.43%, the same as above, then either

   a. Use low-hydrogen electrodes conforming to AWS-ASTM Classification E6015 to E6016, or

   b. Uhe a preheat between 100 and 150°F.

   Alternatively use a steel, other than A7, having a controlled chemistry.

3. Use A7 steel for plates and shapes over 2 inches up to and including 3 inches thick. If the mill report shows the carbon equivalent to be 0.43% or less then use low-hydrogen electrodes, a preheat of 100 to 150°F or a combination of both.

   If the carbon equivalent is in excess of 0.43% then use a preheat of between 250 and 300°F, or low-hydrogen electrodes and 100 to 150°F preheat or higher, according to the analysis and thickness.

   Alternatively use a steel, other than A7, having a controlled chemistry, with or without low-hydrogen electrodes or a low preheat according to the analysis and thickness.

4. For plates and shapes which are over 3 inches thick, which is not usual in building construction, special provisions should be established based on the foregoing recommendations.

A welding technique should be followed which will prevent weld cracking during welding, as for example, the use of many narrow string beads instead of fewer and wider weave beads for butt welds or multiple passes for fillet welds.

The checking and compilation of mill reports will be very helpful to the fabricator. With some steel mills the chemical limitations previously imposed for A7 steel will be met with only rare exception; with other mills carbon and manganese contents in excess of these values will be usual. Knowing the type of steel to expect from a mill will make it possible to determine the best alternative, which can then be followed as a routine matter. Where only an occasional piece of steel exceeds the chemical limitations, low-hydrogen electrodes or preheat can be used without any appreciable effect on the cost. Where higher carbon and manganese contents are usual, then, preheat, low-hydrogen electrodes or steel with a guaranteed chemistry, all at an extra cost, must be used regularly.

There are many steels with guaranteed chemistry available in standard specifications of ASTM; a few others will be mentioned later for use in bridge construction.

The foregoing recommendations are based on more or less normal conditions.

Stricter requirements should be imposed in designing for special conditions, an airplane hangar, for example, to sit in the middle of the plains of Northern Montana exposed to hot sun and bitter cold, both possibly within 24 hours.

To those with considerable experience with welding, these recommendations may seem to be conservative and needlessly severe. However, they are valid as a general overall basis from which engineers and fabricators can depart in either direction, as their experience indicates.

With Regard to Steel for Bridges

The bridge structure differs from the usual building in several respects; bridge loadings are dynamic and produce stress in one or more of the members many times repeated. These stresses may vary from zero to some maximum value or they may be reversing, going from full or partial tension to full or partial compression and the other way. In addition to these fatigue stresses, high impact stresses may also be imposed on a bridge structure.

More particularly from a welding standpoint, the usual bridge structure is an open framework, exposed to all changes in weather, and principal members are very often of greater thicknesses than are usual in building construction.

The AWS Conference Committee on Welding Bridges has given about as much thought to steels and stresses for highway and railway bridges as any group. The pattern this Committee has set up for allowable stresses for different numbers of repetitions of loading, I believe, will ultimately be applied to all bridge joint designs, regardless of the joining method.

In the 1947 Edition of the "AWS Standard Specifications for Welded Highway and Railway Bridges" article 105 provides the following base metal requirements:

1. Steel conforming to A7 may be used for all joints up to and including 1 inch in thickness without any further limitation.

2. Steel conforming to A7 may be used for joints involving greater thicknesses provided check tests show the carbon content + 16 the Mu content not to be in excess of 0.040%. If this value is exceeded, then the steel must be preheated to 130°F and welded with a procedure which will avoid cracking during welding.

3. Alternatively steel over 1 inch thick may be purchased to Federal Specifications QQ-S-741, Grade A, Type II (Welding Quality). No preheat is required for this steel in thicknesses of 1½ inches and under, but for greater thicknesses, the 130°F preheat previously specified must be used.

4. The specifications do not apply to steel over 2½ inches thick.

The history of welded bridges in the United States, like the history of buildings ,indicates very satisfactory use of A7 steel without any difficulty in service. The record includes an ever increasing number of highway bridges, (mostly girder spans), a lesser number of new railway bridges and a considerable amount of strengthening of existing railway bridges to carry the heavier loads of modern locomotives and cars.

In spite of this favorable record of A7 steel, the Bridge Committee has been studying possible revisions of the stel requirements with the idea of requiring a steel with a controlled chemistry for most, if not all, thicknesses. The Committee feels, and properly so, that the specifications should accomodate the greater use of welding for bridge construction extending to more extreme cases of thickness and weather conditions than heretofor.

Earlier this year the Committee conferred with steel mill representatives in an effort to arrive at practical specifications for the chemical requirements and mechanical properties of a weldable bridge steel. At the same time, the Committee agreed to extend the specifications to cover thicknesses up to and including 4 inches for structural members and not over 8 inches for such incidental parts as shoes, saddles, etc.

The specification requirements arrived at as a result of the conference are as follows:

For Plates the chemistry would be—

	Up to and incl. ½ in.	Over ½ in. up to and incl. 1 in.	Over 1 in. up to and incl. 4 in.
Carbon, max. %	0.27	0.27	0.27
Manganese, %	....	0.50-0.90	0.75-1.15
Silicon, %	....	....	0.15-0.30
Phosphorus, max. %	0.404	0.040	0.040
Sulfur, max. %	0.050	0.050	0.050

These analyses are all ladle analyses, which means that the carbon may possibly be about 0.04% higher in the steel as delivered (check analysis). The silicon content specified for steel over 1 inch thick is to assure a fully-killed steel. While it would be preferable to have a steel made to fine-grain practice this was not found to be practical under present conditions. A fully-killed steel is desirable because of its lower transition temperature and its greater impact resistance at lower temperatures.

The mechanical properties for these plates in all thicknesses were proposed as follows:

Tensile strength 60,000 - 75,000 psi
Yield point 33,000 psi min.
Elongation in 2 in. 22% min.
Elongation in 8 in. 1,500,000/tens. str. % min.

For Structural Shapes the chemistry would be—

For sections having a nominal mean thickness in either the web or flange, whichever is thicker, of 1 inch or less

Carbon, max. % 0.29
Phosphorus, max. % 0.040
Sulfur, max. % 0.050

For sections any part of which exceeds 1 inch nominal thickness

Carbon, max. % 0.29
Manganese, % 0.50-0.90
Phosphorus, max. % 0.040
Sulfur, max. % 0.050

In all cases the mechanical properties of shapes remain the same as for A7 steel as follows:

Tensile strength 60,000 - 72,000 psi
Yield point 0.5 tens. str. or 33,000 psi min.
Elongation in 8 in. 21% min.
Elongation in 2 in. 22% min.

The California State Highway Department prepared the following specifications for the steel used in the viaduct of the Division Street interchange in San Francisco.

For Plates—

	½ in. and under	Over ½ in. up to and incl. 1 in.	Over 1 in.
Carbon, max. %	....	0.25	0.25
Manganese, %	....	0.50-0.90	1.15 max.
Silicon, %	....	....	0.15-0.30
Phosphorus, max. %	0.040	0.040	0.040
Sulphur, max. %	0.050	0.050	0.050

Here again, as in the proposed AWS Bridge Steel, the values are ladle analyses and silicon is specified to assure a fully-killed steel in thicknesses over 1 inch.

The mechanical properties for this steel plate in all thicknesses are as follows:

Tensile strength 58,000 to 75,000 psi
Yield point 32,000 psi min.
Elongation in 8 in. 21% min.
Elongation in 2 in. 23% min. (over ½ in. only)

For Shapes—

For shapes not exceeding 1 inch in thickness A7 steel was specified.

For shapes of greater thicknesses steel conforming to MIL-S-16113 (Ships), Grade HT Steel, was specified. This steel has 0.18% max. Carbon, 1.30% max. manganese and 0.15 to 0.30% silicon. It also contains small amounts of copper, nickel, vanadium, titanium, chromium and molybdenum.

Its mechanical properties are as follows:

Tensile strength 92,000 - 85,000 psi
Yield point 50 - 42,000 psi min.
Elongation 20% min.

The tensile strengths and yield points specified decrease as the thickness increases.

From the standpoint of welding, the California Highway Specifications are preferred over the proposed AWS Bridge Specifications. However, the improvement in chemistry is obtained by the reduction of the yield point from 33,000 to 32,000 psi and a reduction of the minimum tensile strength of 2000 psi from 60,000 to 58,000 with a corresponding increase in the elongation of 1% from 22 to 23% minimum, using the plate specifications as an example.

The AWS Bridge Committee has encountered reluctance on the part of bridge designers to accept these slight reductions in mechanical properties, even on the basis of corresponding reductions in the allowable unit stresses.

(I personally believe the final designs on both bases will produce the same section in most cases.)

So much for the chemistries of these steels. Before leaving them, however, it might be interesting to compare their costs with A7 steel of the same thickness.

The following figures for plate material, show the increase in cost, in dollars per ton, over A7 steel of the same thickness.

	AWS	California
½ in. and under	$ 1.00	none
Over ½ in. but not over 1 in.	3.00	$ 3.00
Over 1 in. but not over 1½ in.	15.00	15.00
Over 1½ in.	5.00	5.00

These extra costs will serve as a guide in deciding whether in any given case it will be more practical and economical to specify a better steel or to use A7 steel and preheat, low hydrogen electrodes and special welding procedures and techniques.

Since the workmanship requirements of the AWS Bridge Specifications have not yet been modified, and since I am unfamiliar with the workmanship requirements of the California State Highway Department, I will offer my own recommendations. Again, with a caution that these suggestions are general and should be made tighter where special circumstances, particularly low temperature service, are involved:

1. For plates and shapes to and including 1 inch in thickness use A7 steel. Get a mill report. If the chemistry is high (carbon, plus 1/6 manganese over 0.40%) use a mild preheat or low-hydrogen electrodes.

2. For plates and shapes over 1 inch up to and including 2 inches in thickness use the California steel without further precautions.
   Alternatively use the proposed AWS steel with low-hydrogen electrodes; or 100°F preheat; or use A7 steel with 200°F preheat; or 100°F preheat and low-hydrogen electrodes. Modify this last suggestion if necessary for the chemistry shown in the mill report and the specific thickness involved.

3. For plates and shapes over 2 inches thick use the California steel with a preheat of 100°F or more; or low-hydrogen electrodes; or a combination of both according to the thickness.
   Alternatively use the proposed AWS steel with a 200°F or higher preheat; or a lower preheat and low-hydrogen electrodes according to the thickness. Preferably do not use A7 steel.

Where welding is done at low temperatures all work should be preheated so that it is at least warm to the hand at least 3 inches on either side of the joint.

To someone hearing all of the foregoing alternatives for the first time, it must certainly seem more futile than trying to fill out a tax return. But like with tax returns, a little study and it becomes quite plain—almost simple!

Economics of Welding

The fact is, that in spite of the extra considerations involved, welding, properly used, may be the most economical way of making structural joints. In the last analysis, the economics will determine what joining method will be used.

Effective and economical use of welding for structural purposes does not depend on the selection of the proper steel alone. The design must be based on use of welding and fabricating operations must be planned to minimize the steps involved in the shop and in the field. Even with an increase in the unit cost of the steel, the total cost may be less because less steel is required or because the total fabricating cost is reduced.

For example, R. E. Robertson, in the Welding Journal, cites a case where 20% of the weight of a truss was saved by eliminating gusset plates and other connection details and welding the joints.

He gives another example of a railroad bridge in which 30 tons of steel were saved by using welded girders and estimates the total saving to be $12,000. (120 ft. long through spans about 10 ft. deep).

J. F. Willis has reported on several occasions on the complete changeover to welded construction by the Connecticut State Highway Department. In one case, he described a deck girder bridge having a 165-foot center span and 2 - 80 foot cantilever end spans, in which 32% of the weight and $6600 were saved by welding the joints.

A 14-story telephone company building in Richmond, Virginia was welded at a savings of $60,000 over a comparable riveted structure.

This by no means is a complete report of the buildings and bridges which have been joined by welding. The number is increasing every day, as more fabricators acquire welding equipment and learn to use it more effectively and as more engineers become better acquainted with welding and the advantages it offers.