EMP Interaction Notes

Note 23

THE PROBLEMS CAUSED BY TACK WELDING REINFORCING BARS IN HARDENED STRUCTURES

by

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ABSTRACT

In reinforced concrete construction, reinforcing bars are usually tied together with wire at various intersection points but at times are tack welded together to hold the bars in their proper array during concrete pouring. Reinforcing steel has also been tack welded together to obtain a degree of electromagnetic-interference shielding from the network of steel in the structure. Here the welding establishes the necessary electrical continuity in the bar system.

However, in structures intended to resist blast or other impact loads, conventional tack welding or other casual welding of the reinforcing bars may create points of weakness in the bars at the welds. The major detrimental effects which may result from tack welding are (1) formation of residual stresses, (2) embrittlement of the steel, (3) creation of stress raisers and (4) incorporation of foreign matter in the weld.

An evaluation of these conditions acting separately and in combination indicates that embrittlement is the most significant source of weakness. The embrittlement results from metallurgical changes in the grain structure caused by the rapid thermal quenching that occurs when the particularly small welds formed by tack welding are made. The reduced strength results from the reduction in ductility and the associated reduction in energy absorption before fracture. Economical design for blast resistance requires that the structure possess the high energy absorption characteristics of ductile action offered by the steel reinforcement within the concrete.

Assurance that the original ductility of the bars will be retained can only be secured by determining the carbon-manganese chemistry of the actual bars to be used, and then using the special welding procedures appropriate to that chemistry and the specific weldment geometry. If the reinforcing bar system is to provide electromagnetic-interference shielding, the welding procedures and weld designs and locations should be specified so that the ultimate strength of the structure will not be degraded.

I. Introduction.

In reinforced concrete construction and especially in the precast-concrete industry, reinforcing bars are often tack welded instead of wire tied to secure the required position of the bars prior to concrete pouring. Reinforcing steel has also been tack welded together to obtain a degree of electromagnetic-interference shielding from the network of steel in the structure. Here the welding establishes the necessary electrical continuity in the bar system.

However, structures which are blast loaded or which carry impact loads causing reinforcing bar stresses close to the yield stress can be severely weakened by conventional tack welding or other casual welding of the reinforcing steel. Recognition of this fact has led to the prohibition of tack welding of reinforcing steel in hardened precast-concrete manholes.[1] The justification for this restriction was quite evident recently when the precast-concrete E Manhole was blast loaded at the U. S. Army Engineer Waterways Experiment Station.[2] The E Manhole is not a hardened manhole and no restriction was placed on tack welding of the reinforcing bars during fabrication. It was noted on examination of the structure after the test that many of the reinforcing bars had failed at the tack welds. Similar experiences that others have reported make it obvious that tack welding or other casual, nonstructural welding creates points of weakness near such welds, but it seems that the exact nature of this weakness in the reinforcing steel is not generally understood.

This memo is a qualitative study of the major phenomena which may result from tack-welding practice. These phenomena are outlined in detail and their effects acting alone or in various combinations with each other are discussed.

Before proceeding further, the term "tack weld" should be defined more precisely. In normal welding terminology, "tack weld" usually refers to a small weld, made in one pass, and of a temporary nature. For example, these welds may be used to position plates or structural shapes for final welding. They may then be removed or incorporated into the final weldment and cease to exist as separate welds.

However, the term "tack weld" in connection with a steel reinforcing bar system refers to generally small spots of weld placed at the intersections of various bars or at lapped splices to temporarily hold the bars in their proper position, or to provide the permanent electrical continuity required for electromagnetic-interference shielding. Such welds, though small and non-structural in function, can have a very pronounced effect on the structural strength of dynamically loaded structures.

From the literature available on welding carbon steels,[3,4,5] specifically reinforcing steels, and from conversation with Mr. P. R. White, of Department 1523, it was determined that the tack-welding operation can cause several possibly detrimental phenomena depending on the chemical composition of the reinforcing bar, the temperature of the bar, the size of the weldment, and several other less important factors. These phenomena are:

1. The formation of residual stresses in the bar due to local expansion and contraction of the weld-affected metal.
2. An alteration of the metallurgical structure of the metal caused by the localized heat of welding and rapid cooling by the base metal, creating a brittle material in and near the weld.
3. Creation of a notch which acts as a stress raiser. This may be a crack in the crater of the tack weld or the configuration of the weld itself.
4. A poor quality weld caused by rust particles, sulphur concentrations, slag inclusions, or other foreign matter. This results in a weld of poor soundness which may crack easily when subject to shock or high stress. These flaws operate in very much the same way as the stress raisers described above.

II. Residual Stresses.

Residual stresses (σ_r) are those stresses which remain in an unloaded weldment after the heat of welding has been dissipated.

The sequence of events whereby residual stresses are created can be summarized as follows:[3] The heat of welding causes local expansion of the adjacent metal in a nonuniform manner because of the high thermal gradient inevitably produced by the high concentration of heat. At this time, plastic deformation is imposed on some of the more highly heated metal by the mechanical restraint to local expansion exerted by the remaining cooler material in the weldment. Then weld metal and material in the adjacent heated zone contract as they cool, but these parts are unable to do so freely or without stress, again because of the restraint of the surrounding cooler metal. Further plastic and elastic strains occur during this cooling and the associated stresses mount rapidly as the yield strength of the cooling metal rises.

Figure 1 illustrates a typical residual stress pattern which results in a bar cross-section along a diameter through the point of a tack weld. These are longitudinal stresses and the residual stress pattern is in internal static equilibrium. That is, the residual tensile force equals the residual compressive force in the cross-section.

The value of the maximum tensile residual stress in a weld area may have any value up to the yield stress of the material (σ_y). However, the residual stresses caused by a small tack weld will ordinarily not be this high.[3] For purposes of discussion, it will be assumed that in this case the maximum $\sigma_r = (1/2)\sigma_y$. If this bar is now subjected to a uniform axial tensile strain, as it would be in a reinforced concrete structure, and if the steel is elasto-plastic as shown in Figure 2, the bar will remain entirely elastic until the applied load reaches the value A $(\sigma_y/2)$, in which A is the cross-sectional area of the bar. At this point, the region of highest tensile residual stress will begin to yield. However, the remaining elastic area of the bar will support further axial load until the entire cross-section yields. This occurs when the stress on the entire area $= \sigma_y$. Since the residual stress pattern was already in equilibrium, this infers that the applied load is A (σ_y). Therefore, the static load at which the entire cross-section of the bar yields has not been changed by the residual stress.

This result will usually hold, unless for some reason there is not sufficient reserve ductility available in the material in the region of high residual stress. When the external load A (σ_y) is applied, all points in the cross-section must undergo a strain of σ_y/E, and some of this strain in part of the cross-section must be plastic. If such ductility is not available, local rupture will occur which will reduce the total load capacity of the bar. This aspect of low ductility is discussed further in the next section on embrittlement.

With regard to rapid and pulsating loadings, Reference 3 states,* "the effect of residual stress under impact loading is not as certain as under static load conditions. Certainly, if notches are present, then residual stresses should be removed from structures subject to impact loads".

It appears then that residual stresses alone are not a problem for static loadings, but in the presence of a stress raiser, these stresses could cause cracking. More will be said of stress raisers (notches, cracks, and flaws) below.

III. Embrittlement.

It is a well known fact in the welding industry that the difficulty in obtaining sound, ductile welds increases with increasing carbon content of the steels to be joined. Concrete reinforcing bars are commonly available in the following three strength grades, and their carbon content is often in the range indicated:

1. Structural Grade - less than 0.3% carbon
2. Intermediate Grade - 0.3% to 0.5% carbon
3. Hard Grade - over 0.5% carbon

These carbon contents are, however, only approximate for the grades given; it is not unusual to find, for example,

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* p. 7.19, First Paragraph.

a bar classified as intermediate grade that has a carbon content of 0.7%. This is because the ASTM[7] specifications for reinforcing bars are based primarily on mechanical test properties and they do not place limits on carbon content. Steel producers are free to provide any composition steel that meets the specified tensile, elongation and bend-test requirements, with a limitation only on phosphorous content. Therefore, it is not ordinarily intended that reinforcing bars be of weldable material.[6,7] Only if the purchaser checks the chemical analysis can he get an indication of the weldability of his reinforcing bars.

The difficulty and expense of reliably determining this chemistry, plus added expense in the welding procedure, can easily far exceed any saving possibly obtained by using tack welding instead of wire tying for bar positioning.

Another factor which affects the properties of a weldment is the temperature of the base metal when the weld is deposited and the resulting thermal gradients. When an arc weld is made in a constructional grade steel, the heat-affected zone experiences peak temperatures in the range of 1300°F to 2700°F and it will, therefore, undergo significant changes in microstructure and mechanical properties.[3] During tack welding, only a very small portion of the base metal reaches these temperatures. This causes a rapid quenching of the weld material and the adjacent base metal by the surrounding cool metal.

Carbon steels within the range of carbon content of concern will form austenite in the hot weld metal.[4] If allowed to cool slowly, the austenite transforms to ferrite and iron carbide, which are the usual constituents of these steels at room temperature. However, if austenite is cooled rapidly enough, or quenched, a new type of structure called martensite appears, which is the essential constituent of hardened steel. It is by this process that martensite can exist in the area of a tack weld made in steel with a carbon content greater than 0.25%.

Martensite can be described as a supersaturated solution of carbon in ferrite. Since martensite has a noncubic structure, and since carbon is still present in the lattice, slip does not occur readily, and therefore, martensite is hard and brittle. Figure 3 illustrates how the hardness of martensite increases with carbon content. This enhanced hardness provides a steel which is extremely resistant to abrasion and deformation.[4] These properties make it apparent why martensite is quite useful in the manufacture of industrial tools, but very undesirable in a reinforcing steel for concrete.

The formation of martensite from austenite requires a rapid rate of cooling, as already stated. This is why martensite will be found in very small welds on relatively large plates or bars, but is not usually found in large welds or in welded connections made with several passes. If the base metal is preheated before small welds are made, slower cooling and less embrittlement will occur. In the case of large weld deposits, the rate of cooling may be slowed enough by the large heat input so that martensite will not form. In welds built up of several passes, some martensite may form when a pass is first made but later passes usually temper the martensite, reducing its hardness and increasing its ductility and toughness. The result then is a weld made up of the best properties of which the steel is capable.[3]

Therefore, tack welding can often result in a small portion of a reinforcing bar becoming brittle. When the structure is later subjected to dynamic loading, the bar tends to be elongated nearly uniformly. If this tack weld is in an area of high strain, it is required to undergo a large deformation in a few milliseconds. The unaffected portion of the bar begins to do this, but the brittle spot cannot maintain continuity with the bar. It cracks, causing a sharp reduction in bar area, a sharp increase in steel stresses, and in many cases, severe local yielding or tensile failure.

IV. Stress Raisers.

The phenomena listed previously under numbers 3 and 4 can be discussed together under the general heading of stress raisers. A stress raiser can be any notch, crack, or flaw that creates a region of stress concentration in a structural element.

If the only effect of a stress raiser were to increase local stress, its consequence in ductile material would not be particularly significant. Initial yielding would simply occur at the highest stress location when external load is applied and, as load is increased, progress across the section until the entire section yields. Thus, as in the case of residual stress, the ultimate load capacity of the cross-section would remain unchanged. However, the local geometry of the material at the point or line of greatest stress concentration is actually such that biaxial or triaxial stress conditions will exist. This characteristic of a stress raiser results in a degree of local restraint to lateral contraction (Poisson's effect) which would not exist in the absence of the stress raiser. This restraint reduces the available ductility so that rupture will occur at somewhat lower strains and possibly somewhat lower loads than would otherwise be sustained.[8] However, the load level at which rupture occurs will be considerably lower if the material is brittle rather than ductile, and the energy required to propagate the crack through brittle material will be <u>very</u> much lower than through ductile material. Thus, brittleness severely aggravates the strength-reducing effect of stress raisers in response circumstances where high energy-absorption is desired before complete rupture.

Tack welding requires a very short duration of welding current and welding rod contact. This action tends to give many tack welds the appearance of small craters. The exterior wall of the crater cools first. As the interior portion cools later and shrinks, it depresses vertically but is laterally restrained by the now rigid exterior wall. This causes biaxial tensile stresses in the crater and often tensile cracks. Therefore, the weld may have a small crack in it even before it is loaded. Under normal conditions, this small crack would not be too serious a problem, but in the presence of the brittle material and impact loading described above, the cracking hazard is enhanced.

Commonly, when only tack welding of the reinforcement is required, very little care is taken to ensure a clean welding surface. Rust or other foreign material may be present on the surface and become included in the tack weld. These particles constitute a flaw or discontinuity in the weld. In the presence of high stress, these discontinuities can cause cracking. Cracking may result from either severe discontinuities and low stress or small discontinuities and high stress.

Another source of cracking in weldments arises from the tramp elements: phosphorous and sulphur.[5] The presence of these elements promotes hot-short* cracking by providing a low melting-temperature, grain-boundary constituent. The tolerance for these elements depends on restraint and thermal-stress considerations since it is the stress at the hot-short temperature that causes cracking.

V. Summary.

The influence on structural performance of each of the phenomena discussed above - residual stress, embrittlement, and stress raisers - depends on the magnitude of the phenomena, the degree to which they are combined, and on the external loading conditions.

Residual stresses alone in ductile material do not have more than a minor effect in reducing the ability of a welded joint to carry impact or dynamic loads.

Stress raisers alone in ductile material can have a varying effect in reducing ultimate blast load resistance, depending on the geometrical severity of the stress raiser.

The existence of brittle material alone (i.e., in the absence of any residual stress or stress raisers) would not be likely to cause failure when loading stress levels and strain rates are low enough so that yielding of that part of the structure is not required. However, where high energy absorption capacity is sought by virtue of ductile response, brittle material alone in high-strain areas can cause very premature failure.

With residual stresses in combination with stress raisers in ductile material, the effects can be more severe than with stress raisers alone, but total energy absorption can remain usefully large. However, where local embrittlement exists, particularly when aggravated by the other two phenomena, the reduction in energy absorption capability can be very significant. This energy absorption capability is essential in the design of economical blast-resistant structures.

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* Brittleness in metal at elevated temperature.

In practical reinforced concrete structures where tack welding has been used, some residual stress and moderate stress raisers will generally exist at the welds. The degree to which embrittlement occurs in the reinforcing steel will depend strongly on the steel chemistry, processing history and welding procedures. Since the most dramatic and severe reduction in blast resistance will occur when embrittlement is severe, and because of the strong role of ductility in keeping energy absorption high in areas of residual stresses and stress raisers, embrittlement should be regarded as the primary cause of failure in tack-welded reinforcing bars.

It should be noted at this point that the "Recommended Practices for Welding Reinforcing Steel, Metal Inserts and Connections in Reinforced Concrete Construction" (AWS D12.1-61) is intended to cover welding performed for structural or strength purposes. In this specification tack welds or spot welds are not mentioned, and from this the inference might be drawn that if the weld is not important structurally then it does not need to be controlled. However, telephone conversations with a member of the AWS committee charged with the reissuance of AWS D12.1 indicate that this committee is aware of the possibly weakening characteristic of tack welding and the addition of a cautionary section to this effect will be considered by the committee.

V. Recommendations.

1. Tack welding of reinforcing bars in lieu of wire tying in hardened structures should not be permitted. There should not normally be any cost penalty in this prohibition unless the contractor does not have experienced wire tyers available, or unless the bar system is improperly detailed or fabricated to allow proper tying. Recommended practices and principles of wire tying are included in the manual "Placing Reinforcing Bars," published by the Concrete Reinforcing Steel Institute, Chicago, Illinois.

2. When welding of reinforcing bars is used for splices or other structural purposes, the provisions of the American Welding Society's "Recommended Practices for Welding Reinforcing Steel, Metal Inserts and Connections in Reinforced Concrete Construction" (AWS D12.1-61), should be closely followed. Briefly, the major requirements in these recommended practices are:

(a) determination of actual base metal chemistry,

(b) use of preheat as determined by the chemistry,

(c) specification of welding process, filler metal, etc., and

(d) use of specific types of weld-joint designs.

3. If the reinforcing bar system is to provide electromagnetic interference shielding, the welding procedures, weld designs and locations should be carefully chosen so that the ultimate strength of the structure will not be degraded. The provisions of the AWS recommended practice (AWS D12.1-61) should be followed as closely as possible. Only structural splice welds are treated in this document, and since a considerably smaller sized weld may be adequate for shielding purposes, it may be necessary to increase preheat somewhat to compensate for the smaller heat input during welding or to make the welds larger than would otherwise be required.

4. Consideration should be given to ordering the reinforcing steel with a limitation on carbon content in addition to regular specification provisions. The resulting reduction in welding expense and difficulty obtained by using a more easily welded reinforcing bar may more than offset the increase in material cost.

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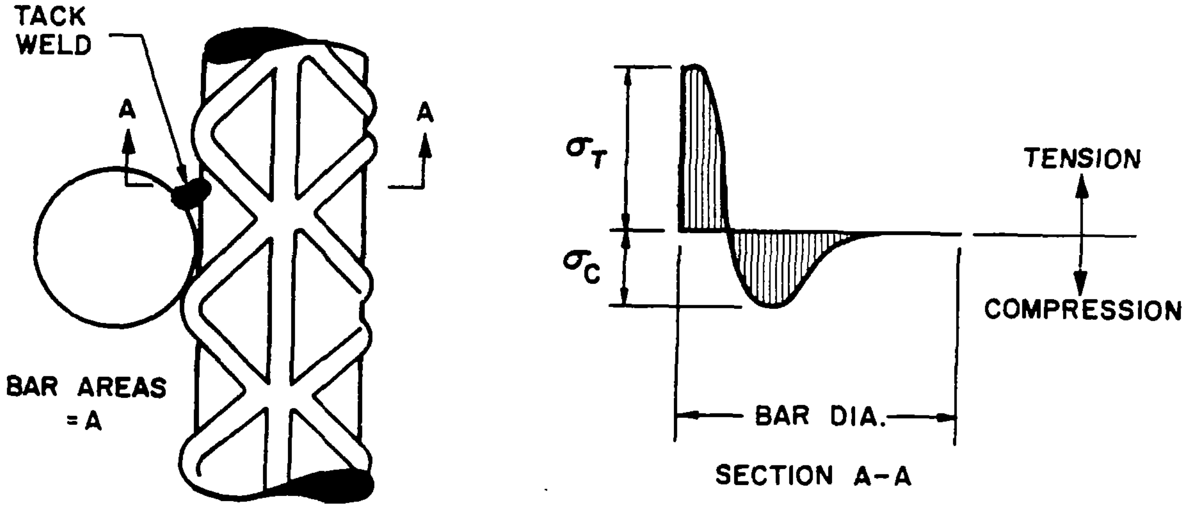

FIG. I

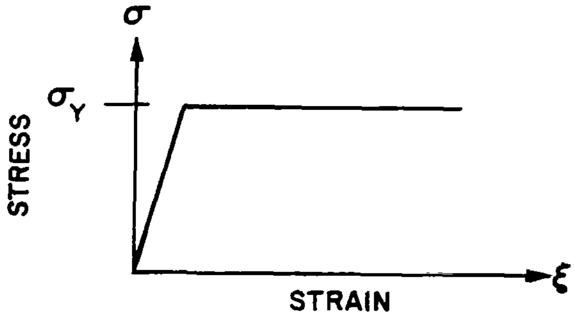

FIG. 2

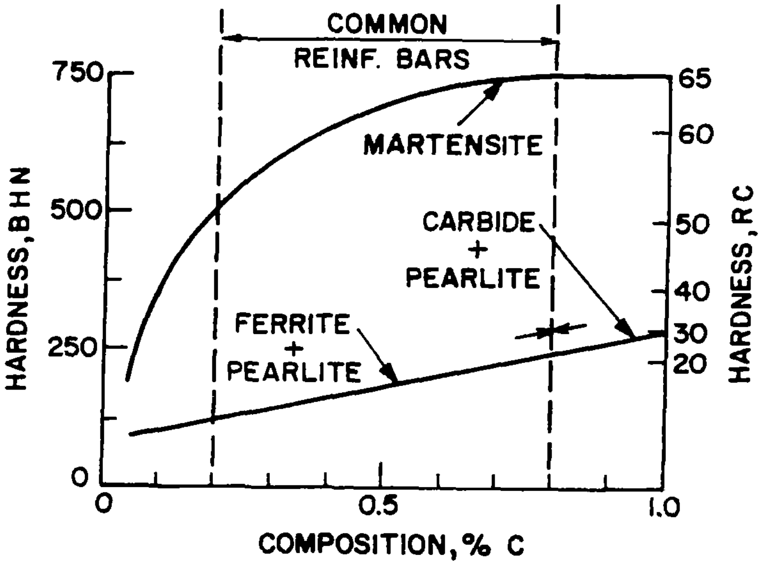

FIG. 3
(FROM REF. #4)