Volume XX, Number 1, 2003

Welding INNOVATION

Advancing Arc Welding Design and Practice Worldwide

A publication of the James F. Lincoln Arc Welding Foundation

Donut Consumption 101

The manufacturing, construction and mining industries that use welding technology together account for about one-third of the U.S. Gross Domestic Product, yet most companies in these fields have never done a thorough study of their welding costs, nor have they ever evaluated the contribution of welding to their complete manufacturing process. The preceding statements are made and supported in a comprehensive study* published jointly last year by the American Welding Society and the Edison Welding Institute.

So fundamentally, when it comes to welding, most manufacturers don't know how much they're spending, or what they're actually spending it on...or even *why.* That's the bad news. Now for the good news: the same study found that companies with a solid understanding of the value welding can add to the manufacturing process, as well as a firm grasp of welding economics, are able to compete successfully, both nationally and globally.

Probably most readers of this publication know the first rule of welding economics—that in the U.S., labor accounts for over 70 percent of total welding expenditures. If welding costs are compared to a donut, by attempting to chip away at equipment and consumable costs, manufacturers are focusing on the hole. The only way to truly reduce costs is to take a big bite of the donut itself—the labor costs. This is done by raising productivity.

Three Ways to Dunk the Donut

Opportunities for increasing welding productivity fall into three broad categories: automation, design and education.

The AWS/EWI study cites automation as the first route to higher productivity, and yet it states, "nearly 60% of all firms reported no effort to actively pursue the automation of welding processes." It observes that most companies wait for industry leaders to take the capital risks of automating, and then only gradually, after seeing proven results, adopt automated methods.

Considering welding requirements should be fundamental to every phase of designing a structure or product. As *Welding Innovation* design consultant Omer Blodgett says, "If the engineer makes the mistake of considering welding to be just another type of fastener, the item or structure as designed will fall far short of its potential capabilities. Welding is not a fastener; it is method of design which, properly used, takes full advantage of the versatility of the material."

Qualified welding personnel are in chronically short supply and almost half of the firms responding to the study said their welding-related training needs are not being met. Manufacturers cited shortages of qualified personnel and a lack of advanced welding education programs at every level of the field, from apprentice welder to engineer.

Taking the First Few Bites

Since 1936, the James F. Lincoln Arc Welding Foundation has been dedicated to enlarging the market for welding by rewarding achievement and sharing technical knowledge. Therefore, we enthusiastically endorse the recommendations in the AWS/EWI study, especially proposed efforts to:

- Develop procedures to help companies understand the economics of adding value by raising welding productivity.
- Identify and pursue improved educational opportunities in the field of welding at local, state, and national levels.
- Coordinate efforts to share knowledge of productive welding practices between and among different industries.

Regular readers of *Welding Innovation* appreciate the fact that many of these objectives are addressed in the pages of this magazine, through such columns as "Lessons Learned in the Field," "Design File," and feature stories profiling a broad range of exceptional projects. So if we're preaching to the choir, please pass this magazine on to someone whom you think might need to hear the message.

Now, Wake Up and Smell the Coffee

When times are good and business is booming, it seems we're always too busy to focus on innovation. And when business is bad, we lack cash to invest in anything that doesn't promise an immediate return. But when it comes to innovation, there is no time like the present. Understand the true economic issues, grasp the fundamental design concepts, and begin a serious study of automation. *Do it now.*

Richard D. Seif,
Vice President, Sales and Marketing,
The Lincoln Electric Company

* *Welding-Related Expenditures, Investments, and Productivity Measurement in US. Manufacturing, Construction, and Mining Industries,* May 2002.

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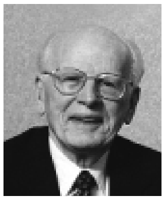
Welding Innovation

Cover: The William Jefferson Clinton Presidential Center in Little Rock, Arkansas features two massive parallel trusses that were fabricated in individual pieces and then assembled in the air, in the vertical position. Photo: Arkansas Aerial Photography. Story on page 17.



Omer W. Blodgett, Sc.D., P.E.
Design Consultant

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The James F. Lincoln
Arc Welding Foundation

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Repair and Maintenance Procedures for Heavy Machinery Components

By Milo Dumovic
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A version of this paper was published at the 50th WTIA Annual Conference held in Sydney, Australia, 26-30 August 2002.

Introduction

Heavy machinery components are subjected to severe destructive conditions of environmental wear. The hardfacing process is a cost-effective tool that can minimize wear and increase service life of heavy machinery components.

Types of Wear

The OECD (Organisation for Economic Cooperation and Development) defines wear as: "The progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface" [1]. Commonly recognized wear categories and their respective estimated shares of heavy machinery wear [2] are shown in Figure 1.

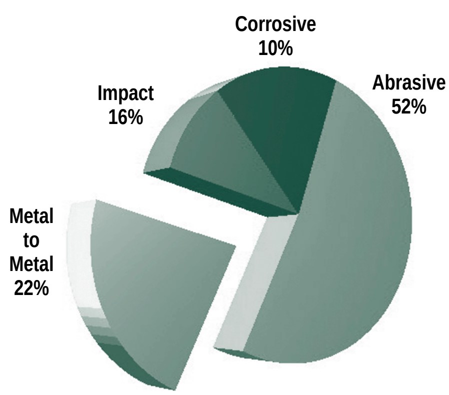

Figure 1. Illustration of the ratio of different wear categories in industry.

Usually, there are several wear mechanisms that act simultaneously on heavy machinery components. The two most common types are abrasive and metal to metal wear.

Metal to Metal Wear

Metal to metal wear occurs when two metallic surfaces slide against each other under the pressure. True metal to metal wear is the most often found under nonlubricated or dry conditions. Archard's Metal to Metal Theory has been widely accepted since the relationship established between the wear volume (V), sliding distance (L), normal load (N) and hardness (H) is consistent with experimentally observed results:

$$V=(KxLxN)/H \qquad (1)$$

K is coefficient of wear.

When shear stresses overcome the cohesive strength of the metal matrix, cracks and voids can be nucleated and wear particles can form [4].

Abrasive Wear

Abrasive wear occurs when non-metallic materials slide or roll, under pressure, across a metallic surface. This type of wear is determined by:

- The properties of the wear material,
- The properties of the abrasive material, and
- The nature and severity of the interaction between the abrasive and wear material.

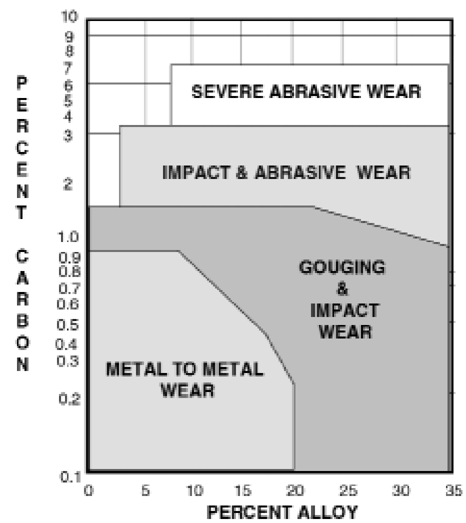

Figure 2. Alloy content as a function of wear. [3]

Abrasive wear can be classified as (a) gouging abrasion, (b) high stress grinding abrasion and (c) low stress scratching abrasion or erosion. In abrasive wear, there are two extreme mechanisms of material removal, one in which plastic deformation plays a dominant role, and the other in which fracture with limited plastic deformation dominates. According to the simplified abrasion wear theory, equation 2, volume loss, Q, is proportional to the applied load (N) and is inversely proportional to the hardness (H) of the abraded surface [5].

$$Q = N/H \qquad (2)$$

Figure 3 illustrates the mechanism of abrasive wear.

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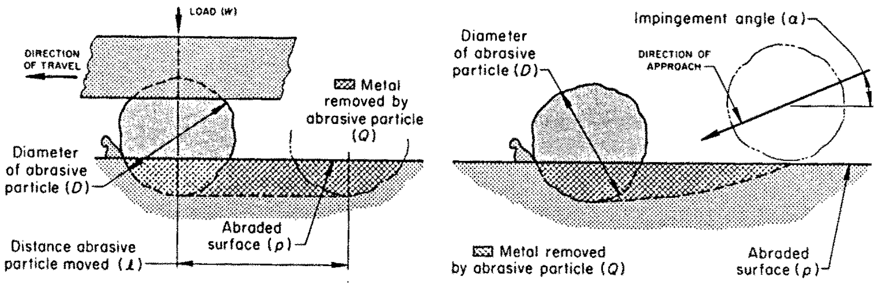

(a) (b)

Figure 3. (a) Idealized representation of abrasive wear resulting from mechanical application of force to an abrasive particle. (b) Idealized representation of abrasive wear resulting from kinetic application of force to an abrasive particle.

Impact Wear

During service, heavy equipment components can also be subjected to impact wear. Toughness can be regarded as the capacity of a material to absorb energy by deforming plastically before fracture. Toughness is independent of the strength and ductility of the material and is measured by Charpy and Izod tests. Table 1 gives the impact toughness of selected materials.

Hardfacing

Hardfacing is a surfacing process used to improve the wear resistance of heavy machinery components without affecting the interior of the component. Hardfacing is a process of applying, by welding, a layer, edge or point of wear resistant metal onto a metal component. Table 2 illustrates engineering methods for surface treatment of steel.

Selection of Hardfacing Wires

Selection of hardfacing wires is based on:

- The wear mechanism acting on the component;
- Tribological conditions: load, temperature and impact;
- Comparison with prior experience;
- Compatibility with substrate materials;
- Requirements for heat treatment and machining after welding;
- Availability of materials, equipment and skilled personnel; and
- Cost.

Table 3 gives the hardnesses of the most common materials used in hardfacing wires.

Table 1. Typical properties of selected materials. [6]

Material	Hardness HV	Impact Toughness (J)
Austenitic (11-13%Mn) Steel	200-250	140
Austenitic (6% Mn) Steel	200-250	30
Cast Martensitic Steel	400-600	15-25
Wrought Martensitic Steel	300-550	20-70
Cast Pearlitic Steel	250-420	5-10
Alloy White Cast Irons	600-900	2-5

Table 2. Engineering methods for surface hardening of steel. [7]

LAYER ADDITIONS	SUBSTRATE TREATMENT
HARDSURFACING Fusion hardfacing (welded overlays) Thermal spray (bonded overlay)	DIFFUSION PROCESS Carburising Nitriding Carbonitriding Nitrocarburising Boriding Titanium-carbon diffusion Toyota diffusion process
COATINGS Electrochemical plating Chemical vapour deposition Thin films (physical vapour deposition) Ion mixing	SELECTIVE HARDENING METHODS Flame hardening Induction hardening Laser hardening Electron beam hardening Ion implantation Selective carburising and nitriding

Table 3. Hardnesses of the most common materials used in hardfacing [8]

Material	Formula	Hardness HV
Ferrite	Alpha-Fe	70 – 200
Pearlite (nonalloyed)	Alpha Fe + Fe3C	250 – 320
Pearlite (alloyed)	Alpha Fe + Fe3C	300 – 460
Austenite Cr- alloyed	Gamma- Fe	300 – 600
Austenite low alloyed	Gamma- Fe	250 – 350
Nickel	Ni	560
Bainite	Alpha Fe + Fe3C	250 – 450
Martensite	Alpha Fe + Fe3C	500 – 1010
Cementite	Fe3C	840 – 1100
Chromium Carbide	CrxCy	1330 – 1700
Titanium Nitride	TiN	1800
Tungsten Carbide	WC	1900 – 2000
Vanadium Carbide	VC	2300
Titanium Carbide	TiC	2500
Boron Carbide	B4C	2800

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Table 4. Influence of alloying elements on the properties of weld deposits.

CARBON	MANGANESE	CHROMIUM
• Reduces ductility (increases brittleness) • Increases tensile strength • Increases hardness • Increases hardenability	• Increases hardness • Promotes a finer grain size • Acts as deoxidiser • Minimizes sulphur, hot cracking	• 1-2% increases the hardness and toughness without loss of ductility • 4-6% increases resistance to tarnishing • Above 11% becomes corrosion resistant • Promotes carbide formation
NICKEL	**MOLYBDENUM**	**VANADIUM**
• Increases strength & toughness • Prevents grain growth • Lessens distortion • Increases hardenability	• Increases tensile strength and toughness • Increases resistance to creep	• Increases tensile strength • Increases resistance to fatigue • Resistant to high stresses

Design and Selection of Hardfacing Consumables

The design and selection of welding consumables for build-up and wear-resistance applications is based on the following principles:

- Addition of carbon;
- Addition of alloys;
- Providing hard particles in a soft weld metal matrix.

Table 4 shows the influence of alloying elements on the properties of weld deposits.

The influence of carbon and percentage of martensite (cooling rate) on the hardness of steel weld metal deposits [7] is shown in Figure 4. The influence of alloying elements on the microstructures of weld metal deposits is given in Figure 5 [9].

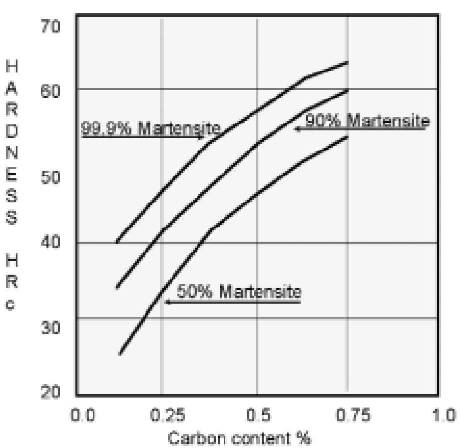

Figure 4. Influence of carbon content and % martensite (cooling rate) on the hardness of steel weld metal deposits.

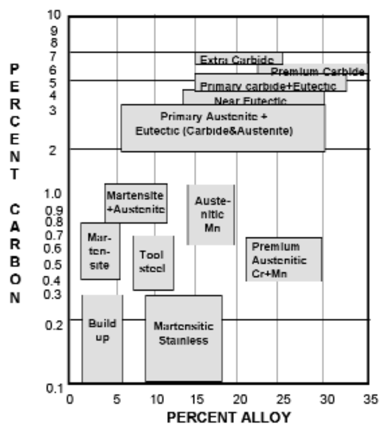

Figure 5. Map of alloying elements and properties of build-up and wear-resistant weld deposits.

Repair Procedures

Preheating

Generally, weld metal and parent metal properties such as chemical composition, hardenability, joint geometry and restraint determine the desired properties for a repaired component. One of the widely adopted approaches for determining weldability is to review the hardenability of the material. The carbon equivalent (CE) formula was developed to indicate how the chemical composition would affect hardenability. The maximum interpass temperature for the repair of austenitic manganese castings is 260°C. Table 5 gives guidelines for preheating temperature as a function of carbon equivalent [10]. The carbon equivalent formula is given in equation 3 [13].

$$CE = C + (Mn+Si)/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15 \quad (3)$$

Table 5. Guideline preheat temperatures as a function of carbon equivalent (CE).

Carbon Equivalent	Suggested preheat (°C)
Up to 0.45	Optional
0.45 to 0.6	95 to 210
Above 0.6	210 to 370

Special precautions should be taken on applications that are crack sensitive, such as high carbon or alloy steels, previously hardfaced parts and highly stressed parts. The repair (hardfacing) of heavy cylinders, massive parts and parts having complex shapes are all examples of applications producing high internal stresses that may result in delayed cracking (Figure 7). These applications may require one or more of the following:

- Higher preheating temperatures 150 to 260°C (Figure 6).
- Higher interpass temperatures up to 480°C. In general this high interpass temperature will not cause a drop in the hardness of weld deposit. Establishing interpass temperatures should also take into consideration the previous heat treatment history of the component.
- Controlled, slow cooling between passes.

Figure 6. Preheat of massive part.

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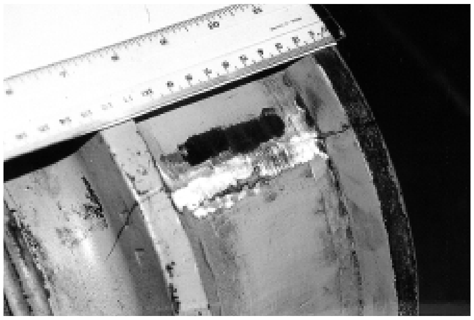

Figure 7. Transverse crack of the repaired idler.

A soaking time of 1 hour per 25 mm of cross section at the recommended temperature is required in order to obtain maximum benefit from preheating. The maximum interpass temperature for the repair of austenitic manganese castings is limited to 260°C.

Postweld Heat Treatment

The iron based hardfacing alloys are among the few engineering alloys that can be heat treated in order to vary their mechanical properties. Heat

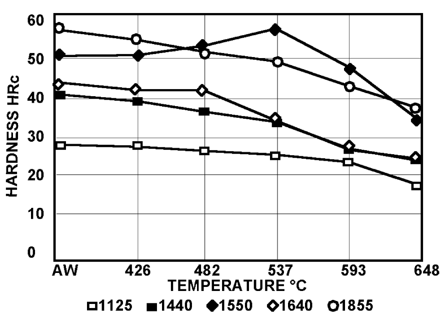

Figure 8. Summary of influence of stress relieving temperature on hardness of weld deposits resistant to metal-to-metal wear (see Table 3).

treatment can be applied to a steel not only to harden it but also to improve its strength, toughness, ductility, decrease the stresses caused by welding and to avoid undesirable microstructures in the heat affected zone. The various heat treatment processes can be classified as : a) annealing; b) normalising hardening; c) tempering; d) stress relieving.

A summary of the influence of stress relieving temperature on the hardness of weld deposits resistant to metal-to-metal wear is illustrated in Figure 8 [11], while a summary of the influence of annealing on the hardness of weld deposits resistant to metal to metal wear is illustrated in Figure 9 [12].

Figures 10 and 11 [12] summarize the relationship between the percentage of carbon and alloying elements and as quenched hardness of hardfacing weld metal deposits.

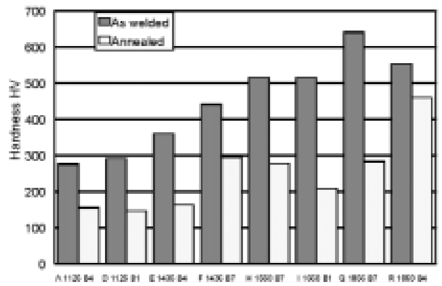

Figure 9. Influence of annealing on the hardness of iron based weld deposits [12].

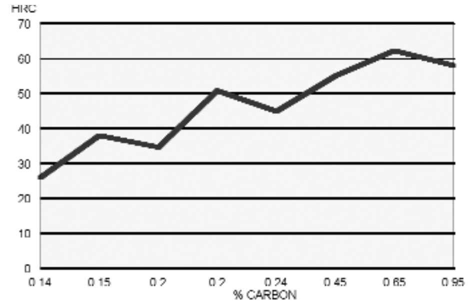

Figure 10. Relationship between carbon content and as quenched hardness of iron based weld deposits [12].

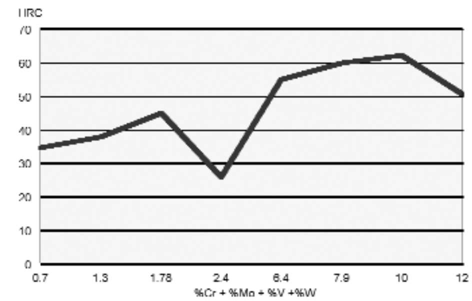

Figure 11. Relationship between total content of alloying elements (Cr, Mo, V and W) and as hardfacing quenched hardness of iron based hardfacing deposits [12].

Examples

Typical Application of a Build-up Product

WIRE CHARACTERISTICS

- Typically less than 0.3%C, less than 6% alloy (Cr, Mn, Mo, Ni);
- Pearlitic/Ferritic weld deposit
- Hardness up to 35 HRc;
- Two distinct applications;
- Provide high compressive strength to support a harder top layer – Build-up layer;
- Final surface for metal to metal wear.

WELDING PROCEDURE

- Preheat 50-210°C;
- Maximum interpass can run as high as 370-430°C;
- Stringers or weave are acceptable;
- Unlimited number of layers;
- Slow cool to avoid cracking;
- Hardness will depend on the cooling rate.

(a) (b) (c)

Figure 12. (a) Idler rebuild; (b) Worn internal surface of dragline chain; (c) chain repaired.

Typical Metal to Metal Wear Application

WIRE CHARACTERISTICS

- Typically less than 0.4%C and 6% total alloy;
- Hardness typically 35-45 HRc;
- Low alloy martensitic weld deposit;
- Austenite transforms to martensite below 371°C;
- Hardness doesn't depend upon cooling rate unless extremely slow;
- Main application is metal to metal wear, especially sliding; also abrasion from softer materials (dirt, limestone).

WELDING PROCEDURE

- Preheat 150-315°C is recommended;
- Max. interpass can go as high as 370-430°C;
- Stringers or weaves are acceptable;
- Usually limited to 3-4 layers maximum;
- Slow cool to prevent cracking;
- Post weld heat treatment required to toughen and soften weld/component after welding.

Figure 13. Shaft repaired using spread arc technique.

Typical Manganese Repair

WIRE CHARACTERISTICS

- Suitable for severe impact applications;
- Typically 0.4 to 0.6 %C, 13 to 20% alloy, mainly manganese;
- Typically 20 to 25 Rockwell C as-welded, work hardens rapidly to 45 to 55 HRC;
- High dilution on mild steel will be martensitic.
- Non-magnetic alloys.

WELDING PROCEDURE

- No preheat required on austenitic base metal;
- Preheat 148-204°C on carbon and low alloy to steel to prevent pullout;
- Limited heat build up to 260°C maximum to avoid embitterment due to Mn-carbide precipitation;
- Unlimited layers;
- No post weld heat treatment required.

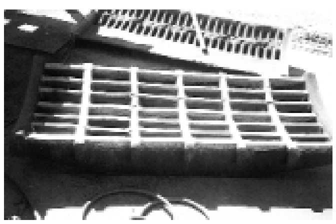

Figure 14. Repaired austenitic manganese steel casting; no preheating applied; maximum interpass temperature was kept below 260°C by immersing component in water bath.

Typical Abrasion and Impact Application

WIRE CHARACTERISTICS

- 2 to 6%C, 14 to 35% total alloy content, mainly chromium;
- Typically 58 to 63 HRC;
- Used primarily to resist abrasion, abrasion & impact – shovel and bucket lips, conveyor screws, blast furnace bells, coal crushers, asphalt mixers etc.

WELDING PROCEDURE

- No preheat on austenitic substrate;
- Preheat at 204°C on carbon steel, low alloy steel, or cast iron;
- First run several beads fast enough to establish tight check crack spacing (6.0 to 19.0 mm) may require ≥1000 mm/min travel speed;
- For a single layer, use heavy overlap (about 70%) to get primary carbides – dilution can lead to primary austenitic or near eutectic structure which has inferior abrasion resistance.

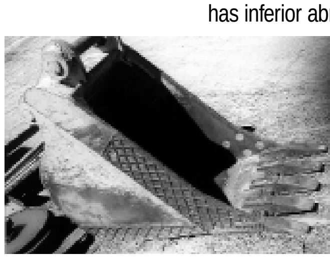

Figure 15. Bucket sides protected with hardfacing.

Summary

Although wear of machinery parts represents a significant economic cost to the owners and operators of heavy equipment, the option of using hardfacing products to restore worn material is a very cost effective alternative to parts replacement. In many cases, the hardfaced deposit will wear better than the original part. The hardfacing solution is successful when the type of wear is properly identified, and the optimal material is selected for the application. Care should be taken to ensure that adequate ventilation and/or local exhaust is used to control operator exposure to welding fumes and its constituents per the material safety data sheet for the consumables being used. Finally, regardless of the hardfacing material selected, the material must be properly deposited to ensure that it performs as intended.

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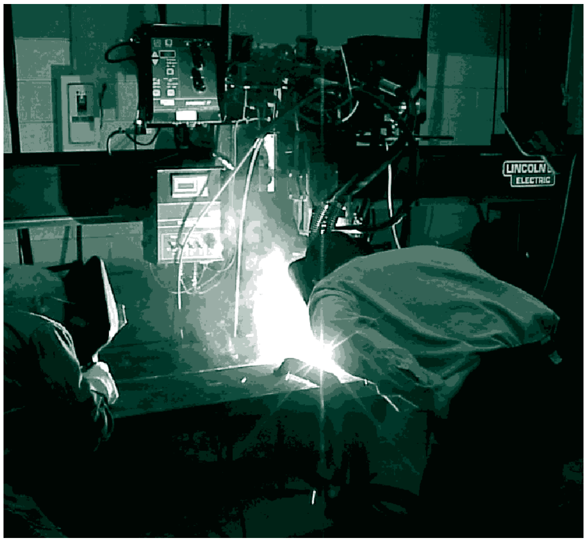
Lincoln Electric Technical Programs



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Design File

Pay Attention to Tack and Temporary Welds

Practical Ideas for the Design Professional by Duane K. Miller, Sc.D., P.E.

Introduction

Ever noticed how sometimes the smallest details can cause the biggest problems? This situation can be compounded when a variable or factor is considered insignificant and accordingly ignored. Such can be the case when tack welds and temporary welds are improperly made.

AWS A3.0 Standard Terms and Definitions defines a tack weld as: "A weld made to hold the parts of a weldment in proper alignment until the final welds are made."

The term "temporary weld" is defined as: "A weld made to attach a piece or pieces to a weldment for temporary use in handling, shipping, or working on the weldment."

The clear difference is that the tack weld joins *"the parts of a weldment,"* whereas the temporary weld joins *"a piece or pieces to a weldment."* Thus, a temporary weld will always join to the weldment something foreign to the weldment proper.

The term implies, but the A3.0 definition does not actually mandate, that temporary welds have a limited life. Specifically, the definition does not require that the weld be removed after its function has been performed. However, the implication is that after the weld and the associated attachment have performed their function during "handling, shipping, or working on the weldment," the attachment and the associated weld will be removed. Thus, the weld that joins a lifting lug onto a weldment could be either a permanent weld (if the lug was to remain in place for future handling of the weldment) or a temporary weld (if the lug was to be removed after handling the weldment). In these two situations, the welds may be otherwise identical, but they are called by different names.

Semantics and definitions aside, the important issue is this: both tack welds and temporary welds must be properly made. Since there are no secondary members in welded construction, improperly made tack or temporary welds may create problems that result in the propagation of cracks into main members. Further, temporary welds may provide the metallurgical path for cracks (if present) in attachments to propagate through the weld, into the main member. Accordingly, these seemingly unimportant welds may be critical, especially in weldments subject to cyclic loading. Let's look into the issues that should be considered when tack and temporary welds are designed and fabricated.

Same Quality Required

In general, the same quality requirements that would apply to final welds should apply to both tack and temporary welds. The *AWS D.1.1: 2002 Structural Welding Code—Steel* requires this in 5.18.1, which states "Temporary welds shall be subject to the same WPS requirements as the final welds." For tack welds, 5.18.2 reads "Tack welds shall be subject to the same quality requirements as the final welds…" The provision goes on to list some exceptions, to be discussed below. But the basic starting point for tack and temporary welds is that they are to be of the same quality as the final welds.

More on Tack Welds

The A3.0 definition does not define the length or size of a tack weld, but rather addresses the purpose of the weld. This definition does not, nor should it, preclude the use of a continuous weld in the root of a joint. It does not, and again should not, mandate a certain maximum size for the tack weld. Colloquial usage would suggest, however, that a tack weld must be small, and intermittent. But as we will see, small intermittent welds may be undesirable in some circumstances.

Tack welds may be placed within the weld joint, and then subsequently welded over with the final weld. Alternately, tack welds may be made outside the weld joint. For welds made within the weld joint, the tack weld may be complete-

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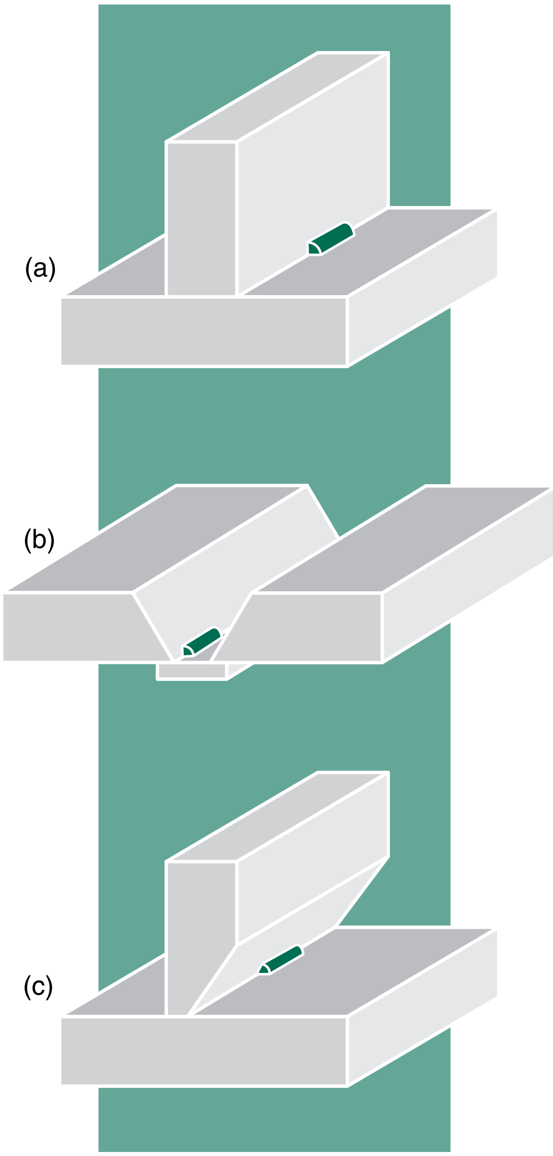

Figure 1. Tack welds in joints.

ly remelted and become part of the final weld. Alternatively, part or most of the tack weld may remain within the joint, and become part of the final weld. Tack welds made outside the joint may remain in place, and become part of the permanent weldment, or they may be removed after the joint has been partially or completely welded. The placement of the tack weld, its relationship to the fill passes in the weld, and the final disposition of the tack—all will affect how the tack weld is to be treated.

A tack weld must be sufficiently strong to resist the loads that will be transmitted through it. Some weldments have individual components that are massive, and the weight of such parts may be transferred through tack welds while the weldment is handled during fabrication. Careful sizing of tack welds that are used for this purpose is essential. Tack welds are often required to hold parts in alignment while assemblies are being preheated for final welding. Thermal expansion, the corresponding strains, and resultant stresses may necessitate tack welds of significant strength. The strength of tack welds, like other welds, is proportional to the throat size, and the length. Thus, a stronger tack weld may be made by making it with a larger throat, or longer length, or both. In most cases, tack welds are intermittent, and the strength across the joint can be made greater by increasing the number of intermittent tack welds, even to the point of a continuous tack weld. Other factors, discussed below, should be considered when determining whether the tack weld should be made longer, or larger, when additional strength is required.

Tack Welds Within the Joint

Examples of tack welds within a joint, shown in Figure 1, would include:

- A tack weld in a T-joint that will receive a final fillet weld
- A tack weld in the root of a CJP groove weld preparation that attaches the steel backing
- A tack weld in the root of a PJP groove weld preparation

In each case, the final weld is placed over the tack weld. The subsequent weld passes may totally remelt the tack weld, and significantly reheat the surrounding heat affected zone (HAZ). Or, the following passes may partially melt the tack weld, and reheat the surrounding HAZ, but the reheating may be to a level such that the previous HAZ properties are not much changed. The first condition will be referred to as "remelted tack welds" and the second as "incorporated tack welds." Fundamentally different approaches should be taken to remelted versus incorporated tack welds.

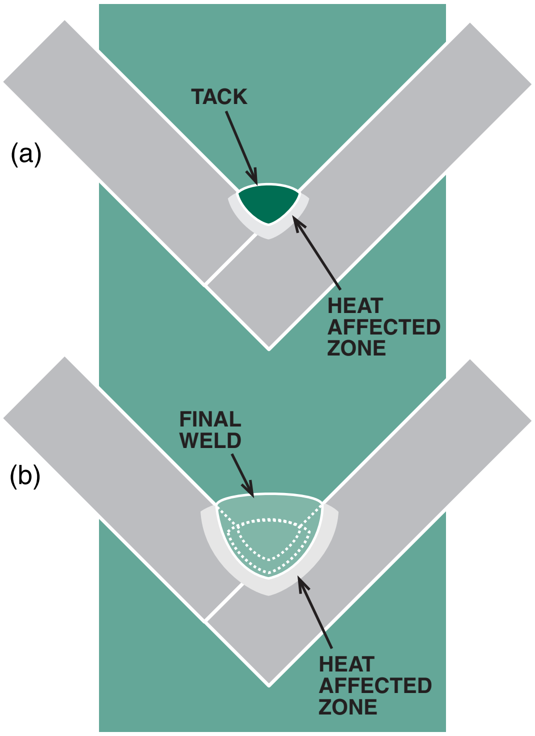

Figure 2. Remelted tack welds.

Remelted Tack Welds

The basic concept behind remelted tack welds is that the subsequent weld passes will effectively eliminate all evidence that the tack weld ever existed (see Figure 2). Accordingly, it is reasonable that quality criteria associated with tack welds that will be remelted would be more relaxed than for the situation where the tack welds become part of the completed weld. This is reflected in D1.1 as follows:

5.18.2 General Requirement for Tack Welds. Tack welds shall be subject to the same quality requirements as the final welds, with the following exceptions:

(1) Preheat is not required for single-pass tack welds which are remelted and incorporated into continuous SAW welds.

(2) Removal of discontinuities, such as undercut, unfilled craters, and porosity before the final SAW is not required.

The two exceptions apply only for the conditions of (a) remelting and incorporation, and (b) subsequent welding by SAW (submerged arc welding).

It should not be assumed that remelting will automatically occur when SAW is used. With the high amperage levels typically associated with larger electrode diameters, remelting may routinely occur. However, SAW may be performed with smaller diameter electrodes, composite (cored) versus solid electrodes, DC- polarity, long contact tip to work distances, lower current levels, and other conditions that may inhibit the ability of the SAW process to remelt tack welds.

Nor is it appropriate to assume that other welding processes cannot remelt tack welds. Electroslag (ESW) and electrogas (EGW) are obvious examples of deep penetrating processes where tack welds are expected to be remelted. While D1.1 does not permit the consideration of other welding processes for remelting tack welds, for work not governed by codes with such a restriction, the capability of other processes could be evaluated. The AWS/AASHTO Bridge Welding Code D1.5: 2002, for example, recognizes the remelting capability of ESW and EGW and extends the exception to these processes as well (D1.5: 2002, 3.3.7.1[1]).

Heavy sections of steel, and higher strength steels with their corresponding higher carbon and/or alloy levels, typically require preheat. Maintence of WPS (welding procedure specification) preheat levels is required for tack welds, unless the exception conditions are met. Even though a small tack weld on non-preheated thicker sections may result in a hard, crack sensitive heat affected zone around the tack weld, the high heat input levels of SAW passes that remelt the tack welds will also reheat the HAZ. If the HAZ created by the tack weld is heated above the transformation temperature, and permitted to slowly cool, the hard, crack sensitive HAZ will be softened. Discontinuities in the tack weld that will be remelted are not a concern, as the remelting process eliminates the discontinuities as well.

If the intent is to remelt the tack weld, then the tack weld should be made with a geometry that is conducive to remelting. Remelting is facilitated when the tack weld is relatively small. Large tack welds are more difficult to remelt, and excessively large tack welds will not be remelted even with high energy SAW procedures. Thus, to gain the required joint strength with tack welds that will be remelted, emphasis should be placed on making small welds that are longer in length. Not only will this encourage remelting of the tack weld, it also minimizes the tendency to disrupt the surface appearance of the final weld.

Incorporated Tack Welds

When tack welds are placed within the joint and not remelted, they are automatically incorporated into the subsequent final weld (see Figure 3). When this is the case, the tack weld should be treated in a manner much like the root pass of a final weld: everything associated with an incorporated tack weld should be the same as would apply to the weld root pass. The preheat, filler metal selection, WPS parameters, weld size, heat input, and the quality of deposit should meet the same standards as would apply to the root pass. In terms of quality, this would include undercut levels, porosity limits, bead shape criteria, and the absence of cracks. Remember: these tack welds will be incorporated, and therefore, will be part of the final weld.

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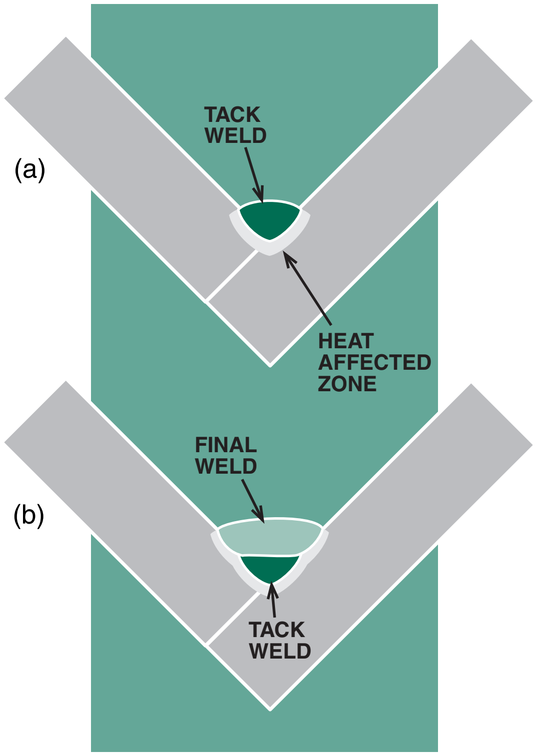

Figure 3. Incorporated tack welds.

A major shift in thinking is required when tack welds are to be incorporated, as compared to the remelted alternative. For example, incorporated tack welds should be made of a size, and with a heat input level, that will ensure good fusion. These welds should meet the minimum size requirements that would be imposed on any final weld. This will naturally result in larger sized tack welds than was encouraged for remelted tack welds. Thus, for a required joint strength, incorporated tack welds will be larger in size, but perhaps shorter in length, as compared to the remelted option.

Large, intermittent tack welds may require that the gaps between the tack welds be completely welded before the subsequent layers are made. Welding over large tack welds may disrupt the arc, or may affect the appearance of the subsequent final weld. The ends of the tack weld may be points where fusion into the weld root is difficult to achieve. Thus, the acceptable geometry of the tack weld is dependent on the ability of the final weld procedure to properly incorporate the tack weld into the final weld. This is the reason, for example, that 5.18.2.1 of D1.1 requires that multipass tack welds have cascaded ends.

Considerations for Both Types of Tack Welds

Irrespective of whether the tack weld will be remelted or incorporated, the interaction of the tack weld and the final weld must be considered. Tack welds are often made with a different welding process, or even when the same process is used, with a different filler metal than will be used for the final weld. Chemical interactions between the two types of materials should be considered.

Some self shielded flux cored arc welding (FCAW-S) filler metals will have slag removal problems when welding over tack welds made with certain shielded metal arc welding (SMAW) electrodes. The electrode manufacturer can be contacted for a list of compatible electrodes.

A second type of interaction that must be considered is the potential effect of intermixed weld metals on mechanical properties. The Charpy V-notch toughness of subsequent final passes of normally tough welds may be reduced due to negative interaction with tack welds made with welding processes using a different shielding system. The typical combination that should be investigated is when FCAW-S is used to tack weld under non-FCAW-S deposits, such as SAW, or gas shielded FCAW. This does not mean that all combinations are unacceptable. However, these should be investigated on a case-by-case basis. The James F. Lincoln Foundation publication *The Fabricator's and Erector's Guide to Welded Construction*, available as a free PDF download from *www.jflf.org*, addresses a variety of combinations.

Tack Welds Outside the Weld Joint and Temporary Welds

When tack welds are placed outside the weld joint, and for all temporary welds, other factors must be considered. Simply put, these welds too should be treated as any final weld. They should be made with materials, procedures, techniques and quality levels that would be acceptable for final welds. Tack welds outside the weld joint fit into two categories: permanent, and removed. Temporary welds, by definition, will be removed.

Permanent Tack Welds Outside the Weld Joint

Tack welds outside the weld joint must be evaluated to determine if they can remain in place without causing unintended consequences. Of necessity, D1.1 places this responsibility on the Engineer as follows:

5.18.2.3 Nonincorporated Tack Welds. Tack welds not incorporated into final welds shall be removed, except that, for statically loaded structures, they need not be removed unless required by the Engineer.

Thus, for statically loaded structures, the normal practice will be to leave such tack welds in place, unless otherwise indicated by the Engineer. For dynamically loaded structures, such nonincorporated tack welds would be removed.

Consider the potential tack welds that could be used to attach longitudinal backing under a CJP groove weld. One option would be to tack weld the backing in the root of the joint as shown in Figure 1b. This may pose some practical problems, prompting the need to tack weld the backing outside the joint. Intermittent tack welds would be sufficient to hold the material in place, as shown in Figure 4a. This would be an acceptable option under D1.1 for statically loaded members. However, if the same member was put into a cyclic loading situation, the intermittent tack welds would behave as Category E fatigue details, greatly limiting the allowable stress range. An acceptable alternative (although not one specifically given in 5.18.2.3 of D1.1) is to make a continuous tack weld, which would behave as a Category B detail, much like the longitudinal CJP groove weld (Category B) shown in Figure 4b.

It is good to remember the adage "There are no secondary members in welded design" when evaluating the suitability of leaving in place tack welds that are made outside the weld joint.

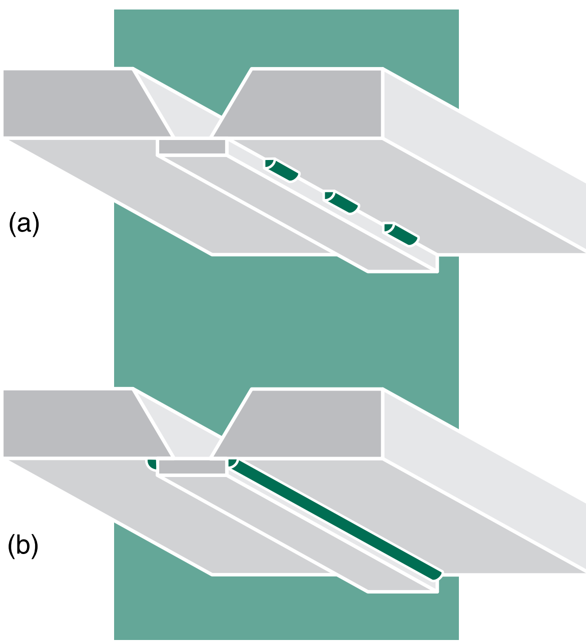

Figure 4. Non-incorporated, intermittent (a) and continuous (b) tack welds.

Removing Tack and Temporary Welds

When tack welds are required to be removed, and when temporary welds are removed, it is important that that the weld be fully removed *without damaging the base metal.* A typical approach is to thermally cut the weld or attachment off (using air arc gouging, oxy fuel cutting, or plasma cutting), and follow up with grinding. When cutting is performed too close to the final surface, one may inadvertently gouge the base metal.

The procedure described above assumes, however, that the tack weld, or the temporary weld, was properly made in the first place. Consider the improper procedure wherein a tack weld is placed outside the joint, but the weld is made without preheat, or the needed minimum heat input, or with an improper electrode. Such a procedure could result in an underbead crack, an excessively hard HAZ, or other weld defects. Simple removal of weld metal from the surface of the steel will not automatically remove the defect that may reside in the base metal. This can result in performance problems for the weldment, particularly when subject to cyclic loading.

In the case of Fracture Critical Members (FCMs), D1.5 requires that, when weld removal is required, the weld plus 1/8 in. [3mm] of adjacent metal be removed. The surfaces are faired in at a slope not steeper than 1 in 10 on the surface (see D1.5: 2002, 12.13.3). This conservative provision ensures that the whole weld, plus any affected base metal, is completely removed, along with any unacceptably hard or cracked material.

Summary

Neither tack welds nor temporary welds should be viewed as inconsequential, secondary welds, particularly when applied to cyclically loaded weldments. Whether the tack weld is to be made in the joint or not will affect the overall approach to the weld. If it is made in the joint, whether the tack weld is to be remelted or incorporated will determine the ideal configuration for that tack weld. For tack welds and temporary welds that will be removed, care must be taken to protect the base metal. There are plenty of opportunities to make tack and temporary welds improperly. Fortunately, it is not difficult to make them correctly.

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Lessons Learned in the Field

Understanding Distortion is a Never Ending Challenge

By Byron Horn
Welding Specialist
Michelman-Cancelliere Iron Works, Inc.
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The Project

My company was asked to fabricate sixteen catcher beams to be installed on the Commodore Barry Bridge outside Philadelphia. In the event that the main pins that carry the deck of the bridge should ever break, these beams are designed to "catch" the deck and keep the bridge from plunging into the water. The creation and installation of the catcher beams was part of a retrofit project on the bridge, which was built in 1974 and is owned by the Delaware Port Authority. The project was completed in November, 2002.

Background

The steel selected for the catcher beam project, a 2 in. [50 mm] thick A710 Grade A Class 3 material, was chosen for its high Charpy value, 60 ft-lbs [80 J] at minus 80°F [minus 62°C]. When I tried to develop a history of the A710 steel, information was very limited. I could not find that it had ever been used on a bridge anywhere in the United States. The U.S. Navy had used A710 in the past, but had a history of it cracking at thicknesses greater than 1 in. [25 mm].

The structure of each catcher beam consisted of a box with two flanges 2-1/2 in. thick by 17 in. [65 mm by 430 mm] wide and two webs that were 2 in. thick by 18 in. high [50 mm by 460 mm]. The outside corner welds were 1-3/8 in. [35 mm] partial joint penetration (PJP) groove welds, with an inside corner weld of 3/8 in. [9.5 mm]. This of course was only on the bottom flange, which could be welded inside. Once the cap was put on, welding was restricted to the outside, dictating PJP groove welds only.

The Initial Challenge

With this very limited information, I put together a game plan according to which we would preheat and rotate this assembly after it was tacked up. We built a preheating station in which the part could be heated and rotated. It became known as the "rotisserie." We brought the beam up to 400°F [200°C], let it soak for one hour at that temperature, then let the weldment cool down to 350˚F [175˚C], before welding the first root pass on the two bottom outside partial joint penetration groove welds. After that, the spreader beam was taken out of the rotisserie, and we ran the two inside 3/8 in. [9.5 mm] fillet welds. The temperature was still maintained at 350°F until the completion of the 3/8 in. fillet. Then the assembly was allowed to cool down to room temperature.

> The zero clearance tolerance proved to be a real challenge

Now the spreader beam was fitted with six internal bearing stiffeners. Both ends of the stiffeners had to have a mill-to-bear fit to each flange, and no weld was initially specified. The mill-to-bear tolerance was zero clearance across the full width of the stiffener. Anticipating that this fit requirement would be difficult to achieve, we fabricated a yoke-type fixture to tightly clamp the stiffener to the flange. The fixture ensured that this fit was maintained before welding began.

Despite the fixturing, the zero clearance tolerance proved to be a real challenge. We would start to weld, and the stiffener would start rising out of the box, creating a 0.015 to 0.020 in. [0.381 to 0.508 mm] gap. We changed the direction of welding, and tried driving the weld in from the outside corner. Ultimately, we ended up running a short 6 in. [150mm] weld, skipping a 6 in. space and completing the joint by using a back-step welding technique to complete the fillet welded joint.

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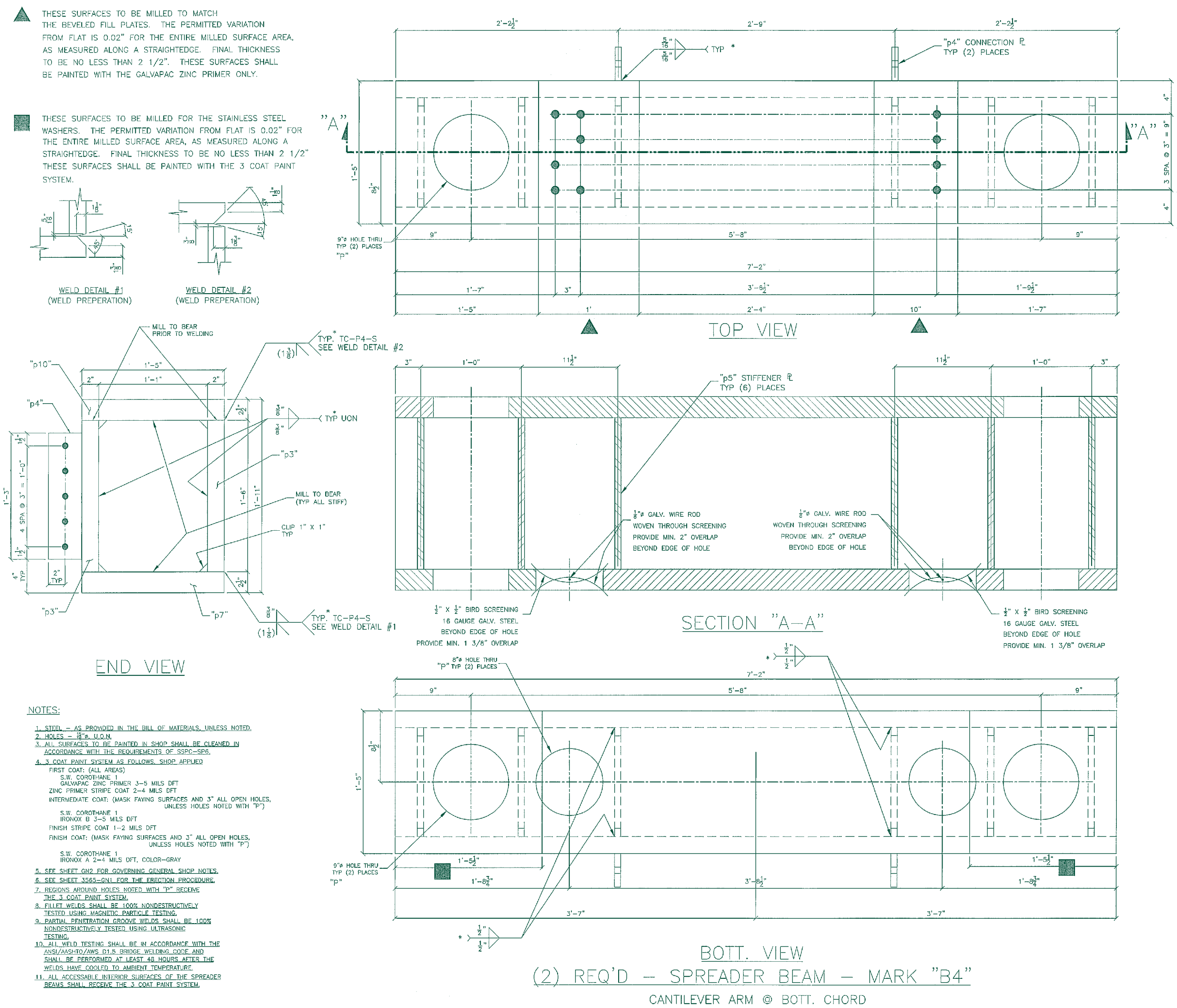

We also used differential preheat to control this dimension. We only preheated the web, with no direct heat applied to the stiffener. The stiffener received its 250°F [120°C] preheat via heat conduction through the web. The 100°F [40°C] differential allowed the web volume to expand to a greater dimension than the stiffener. Then, after welding and overall cooling, the web volume contracted more than the stiffener volume, which drove the stiffener into contact with the bottom flange.

The combination of the welding sequence and the differential preheat were sufficient to get the stiffener into continuous contact with the flange. At this point, one consultant we spoke with about the project remarked, “You might as well be making a Swiss watch out of a steel beam!” It certainly felt that way at times. But our problems still were not over.

Another Problem

The surface of the flange plate wasn’t flat enough for the tolerance. We discovered that the way these plates came from the steel mill, there was a very slight waviness and grooves on the surface of the plate, and that accounted for the 0.015 in. [0.381 mm]. Since the plate surface rolling tolerances exceed 0.015 in., no amount of preheat temperature differential between the web and stiffener could correct the out of tolerance gaps. We went back to the Engineer, who raised the tolerance to 0.010 in. [0.54 mm]. Still, we had rejections. Then the Engineer raised the tolerance to 0.015 in. [0.381 mm]. More rejections. So we ended up receiving permission from the Engineer to weld the bottom of the stiffeners to the flange.

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Now, The Top Flange

To control the gap between the stiffener and the top flange, both components were machined in a big planer to a flat and level condition.

On the first spreader beam that was welded, the top flange distorted in a convex direction approximately 0.030 in. [0.76 mm]. To reduce this distortion we used a post heat of 350°F [175°C] for a minimum of 8 hours. The post heat relaxed the welding residual stresses to a point where the flange flattened down to under 0.015 in. [0.381mm].

The other thing I did to control distortion was to build in a 0.010 in. [0.254 mm] gap between the flange and the web, fixing this dimension by using small tack welds. The tacks created a gap which gave room for the shrinkage, to bring the top plate down before it started to distort. Creating this small gap did about as much for us to control distortion as anything. The heat definitely helped flatten the flange out over time, but the small gap gave it some place to go.

Hydrogen Control

The second challenge was to prevent delayed weld cracking by controlling hydrogen in the weld. This was done via two methods:

First, we used a controlled hydrogen process: SAW (Lincoln Mil800-H flux and LS3 wire combination) with diffusible levels between 1.5 to 2 ml/100 grams of weld deposit.

Second, we filled each partial joint penetration groove weld to only half of its depth before rotating to the next joint. Hydrogen takes time to diffuse, and the greater the distance of material through which the hydrogen must travel, the more time will be required. By welding only half the groove depth, the distance for hydrogen to diffuse was reduced. Also, since the whole assembly was maintained at the preheat/ interpass temperature, the rate of hydrogen diffusion was greater. While hydrogen was diffusing from the partically welded joint, another joint was welded.This allowed a minimum of 12 hours for the diffusible hydrogen level to drop even lower. This procedure also balanced some residual stresses, controlling distortion (sweep and camber) of the beam assemblies.

Making a Swiss watch out of a steel beam

Personnel with whom I had spoken at two Navy shipyards described delayed cracking in welds over 1 in. [25 mm]. I believe that if the shipyards had followed the above with proper preheat practices and the use of low to medium restrained joints, weld cracking would have been reduced to an acceptable level.

Conclusion

Despite the demanding conditions, the project was completed successfully. By using principles of distortion control, the displacements were minimized, although the final solution required the application of a fillet weld to overcome all the challenges. A cooperative Engineer and careful planning overcame the dimensional control problems. Selection of the proper materials, control of procedures, and careful preheat and interpass temperature controls overcame any tendencies toward hydrogen cracking. I guess we did make a Swiss watch out of a steel beam.

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Making the Essential Connections on "A Bridge to the 21st Century"

By Carla Rautenberg
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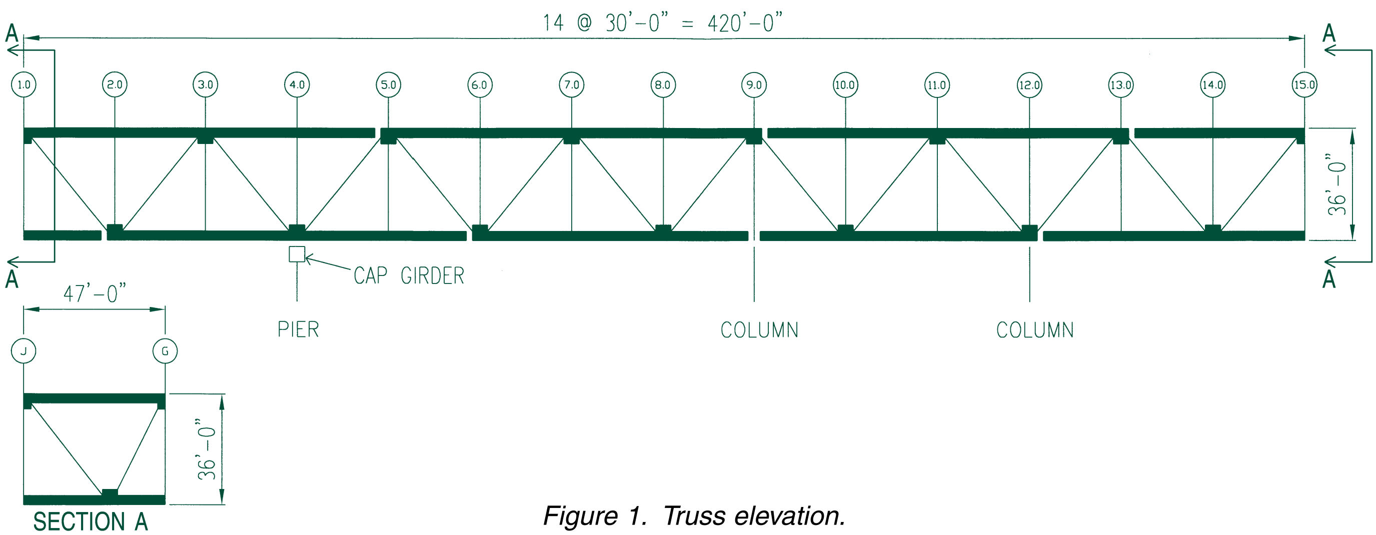

Figure 1. Truss elevation.

Background

The building permit cost $185,000. The field erection consumed 1.1 tons [0.99 tonnes] of welding electrode. In another year, the structure will hold more than 80 million pages of documents, 40 million e-mails, 2 million photographs and almost 80,000 artifacts. When it opens in November 2004, the $160 million William Jefferson Clinton Presidential Center is expected to put Little Rock, Arkansas on the map as a tourist destination. For the employees of AFCO Steel of Little Rock, Arkansas, the company that fabricated the structural steel for the building, the project holds special meaning. According to Bob Bendigo, V.P. of Operations at AFCO, "The people who build our projects in the plant are seldom able to see them go up. But in this case, we all drive by it every day, coming to and from work.

The plan required the steel pieces to fit together perfectly the first time

And that caused a heightened interest in the project, and a pride that went along with that."

The long, slender building elevated above a park was designed by the Polshek Partnership of New York to express former President Clinton's favorite theme for his administration, that it was "a bridge to the 21st century." The oblong design also echoes the six bridges that span the Arkansas River in Little Rock. In addition, Architect James Polshek incorporated an existing (now unused) railroad bridge into the site design; it will be renovated for pedestrian use. The circa 1899 Choctaw railroad station depot building adjacent to the presidential library is being renovated to house the Clinton School for Public Policy, which will grant master's degrees in public services starting in 2004. A 30 acre [120,000 m^2] park featuring an amphitheater, a children's playground, and trails for walking and bicycling, is the site for the entire complex.

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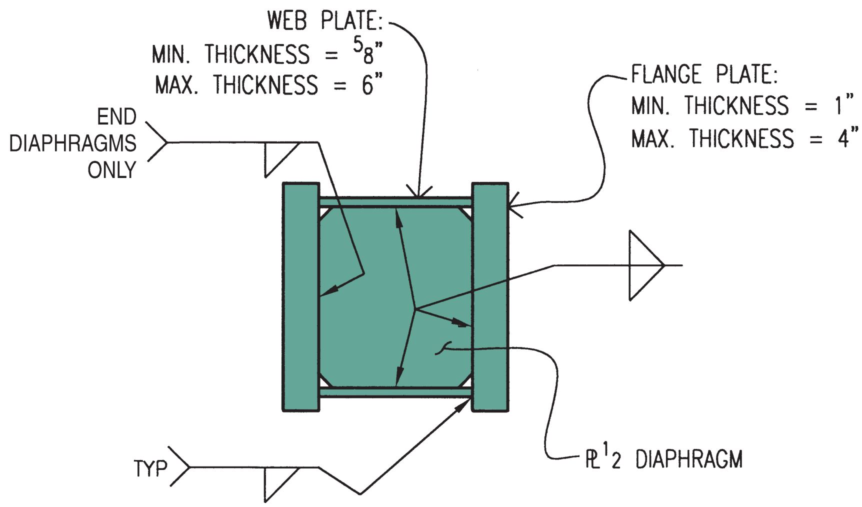

Figure 2. Typical truss member section.

Developing the Game Plan

The library's design called for two large parallel trusses, 420 ft. [128 m] long, and 36 ft. [11m] tall. With supports at only three locations, the two ends of the building were designed to cantilever out 90 ft. [27 m]. On the north end of the building, a massive steel pier supports the structure. This design not only created the architect's vision of a bridge, but also resulted in bridge-like members for the steel fabricator to build.

When AFCO Steel won the contract to fabricate the structural steel for the Clinton library, the company knew that all of its planning would flow from the methodology selected to erect the structure. Proposals were submitted by four erectors, all of whom had comparable qualifications. But according to Gary Johnson, V.P. of Contracts for AFCO, "This job was so unique, no one could say, 'Yeah, I've built some of those before.' So we had as many different schemes to erect this building as we had bids. They were each firmly committed to their own way of erecting the project." In the end, AFCO chose the strategy proposed by Derr Steel Erection Company of Euless, Texas, which called for the truss to be fabricated in individual pieces, then, using falsework, to put the pieces in their proper position and elevation and to assemble the truss in the air, in the vertical position. This scheme modified the normal practice of performing more welding in the shop, versus in the field. And the plan required that the steel pieces would have to fit together perfectly, the first time, if the job schedule was to be maintained.

While the truss design and its assembly on site echoes elements typical of bridge construction (see front and back cover photos), the building of course did not pose the dynamic loading challenges of a bridge. And while bridges are usually field-bolted, this structure would be joined together with field welded connections. Unlike most buildings made principally of wide flange shapes, the library made extensive use of built up, four-plate box sections, fabricated in the shop and requiring very high standards of dimensional control.

Fabricating the Members

The planning for the project had to be meticulous. Every piece of structural steel was custom-fabricated by an AFCO shop crew that numbered from 30 to 40 welders. AFCO's Johnson said the greatest challenge overall was "To maintain the integrity of each piece that we were building, as well as to make the connection preparations that would fit together in the field to complete the truss configuration. Because of their size and weight, we could not lay these trusses down in our shop." To supply the Derr Steel Erection Company with a steady stream of fabricated components in the field, AFCO allowed a 10-week lead time for fabrication of the box sections that would make up the truss chords and braces, and 4-6 weeks for the wide-flange members that were used for floor beams and other members. Johnson noted that at the outset, the planned lead time seemed more than ample, but "in the end, it was just about right. We wouldn't have wanted to do it any faster."

The first truss drawings were issued to the shop on September 3, 2002. Truss fabrication began seven days later and was completed on January 16, 2003. Elements of the complex fabrication task included:

Truss Members

The truss chords consisted of four-plate built-up steel box sections made of A572 Grade 50 and A588 plate. A572 was used for members with thicknesses ranging from 5/8 in. [15 mm] to 4 in. [100 mm], and A588 for thicknesses greater than 4 in., and up to 6 in. [150 mm] (since the A572 Grade 50 specification covers material up to and including 4 in. thick, whereas the A588 specification governs plate up to 8 in. [200 mm] thick). The truss has 30 vertical members, 32 diagonal members, 36 chord segments, and 36 nodes (see Figure 1). The verticals and diagonals were shipped as individual components to be erected at the site. The

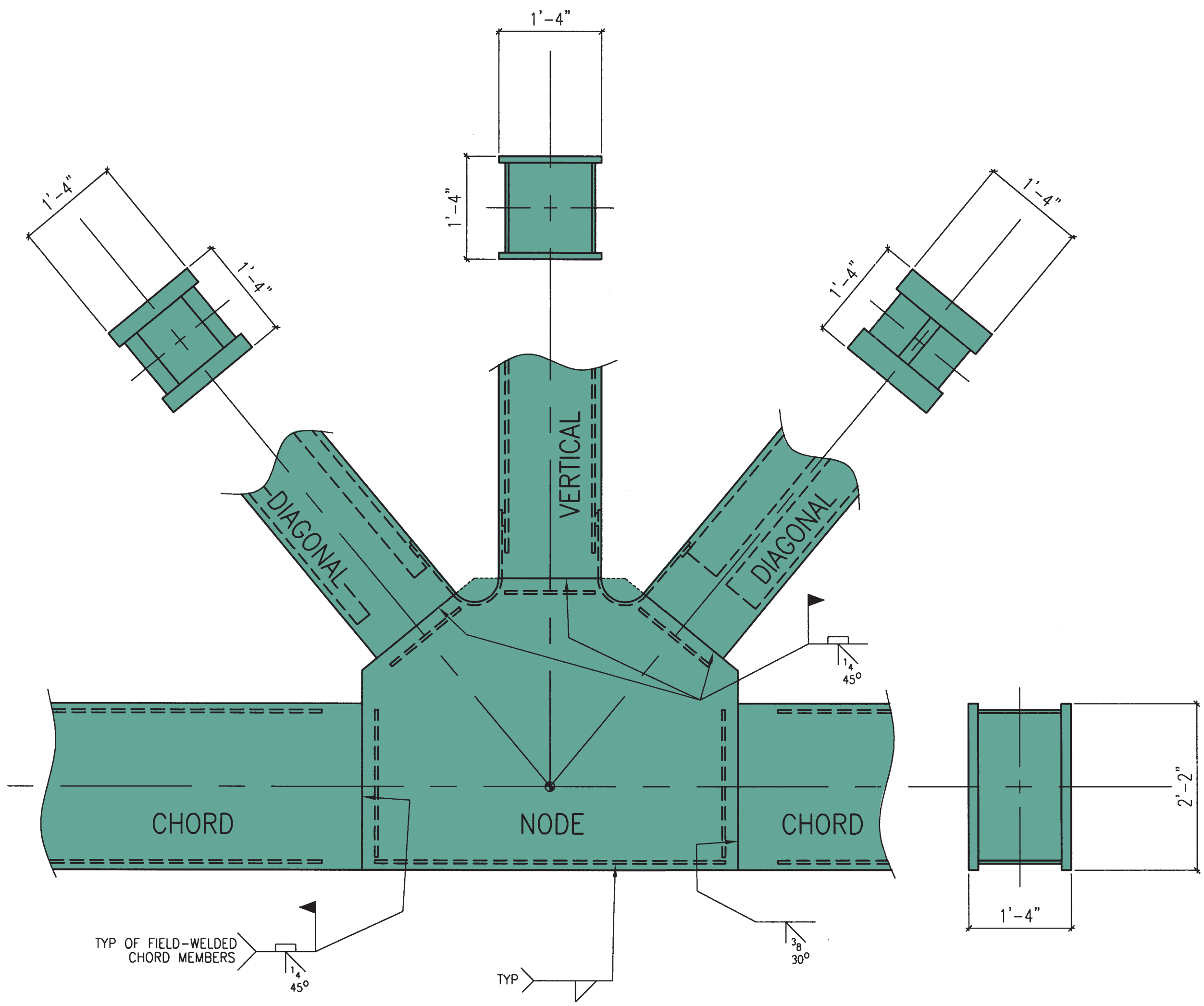

Figure 3. Typical node configuration.

36 nodes and 36 chord sections were shop assembled into 22 shipping pieces ranging in length from 28 to 125 ft. [8.5 to 35 m] long, and weighing up to 40 tons [36 tonnes].

Box Welding

Each four-plate box section required four full-length fillet welds, to fabricate the member (see Figure 2). Fillet welds ranged from 5/16 to 1/2 in. [7 to 13 mm], depending upon the thickness of the plates being joined. The 4,178 linear ft. [1273 m] of box members required 16,712 linear ft. [5,094 m] of shop fillet welding—or a total of 3.2 miles [5.1 km]. Shop welding was performed using submerged arc welding and shielded metal arc welding.

Chord / Vertical / Diagonal to Node Welding

The steel trusses have all welded connections, with the verticals and diagonals connected to the chords at nodes (see Figure 3) using complete joint penetration groove welds in plate varying from 1 to 4 in. [25 to 100 mm] thick. The 36 chords and 36 nodes were shop assembled into shipping pieces using 1,456 in. [37 m] of CJP groove welds. The balance of the welding of the chords/verticals/diagonals to the nodes was completed on site using 6,032 in. [153.2 m] of CJP groove welds field welded in the horizontal and vertical positions. Flux cored arc welding was used in the field.

Support Columns and Piers

The above-grade structure is supported at the center and the south end by four columns that are four-plate built up box sections similar to the truss members. They were fabricated of

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plate in thicknesses of 1-1/2 to 4 in. [38 to 100 mm], are 41 ft. [12.5 m] long and have an average weight of 12.5 tons [11.34 tonnes]. The north support is a steel pier composed of two columns and two cross members that tie the columns together into a single assembly 36 ft. [11 m] tall by 20 ft. [6m] wide. The 72-ton [65.3 tonne] pier was fabricated outdoors due to its size and weight, then shipped to the site as a single unit. The massive steel pier cap shown in Figure 4, fabricated by Capital Steel in Oklahoma City and trucked to the job site, is 15 ft. [4.6 m] deep by 50 ft. [15.2 m] wide and weighs 95.5 tons [86.6 tonnes].

The Field Erection Process

In the field, the greatest challenges were: supporting the structure with falsework towers and bracing, and minimizing distortion to maintain the straightness of the structure.

According to Jeremy Beadles, project engineer with Derr Steel Erection, the 700 ton [635 tonne] weight of the truss was daunting: "With a truss that heavy, it's really hard to design erection aids that can carry the load."

Carl Williams, senior engineer with Derr, described efforts to maintain the straightness of the structure: "We worked out a sequence of welding both sides of each joint at the same time to minimize the welding draw. Then we went through the structure and came up with an overall welding sequence in order to minimize the possibility of it all drawing the structure out of alignment. Our sequences worked well, and we were able to keep the structure in a whole lot tighter alignment than even the Engineer of Record thought we could." Preheats from 150-350°F [65 to 175°C] were used, with some welders arriving at the site at 5:30 a.m. to start the preheating process, ensuring the required temperature would be achieved when the rest of the welders arrived at 7:00 a.m.

The project was managed by CDI Contractors, LLC of Little Rock, Arkansas, and their project manager, Rob Hawkins.

A "Hold Your Breath" Moment

The four-story, 420 ft. [128 m] long building is supported in just three locations, with the trusses on the north and south both cantilevered out 90 ft. [27 m]. AFCO's Gary Johnson pointed out, "In putting the truss together, we were instructed by the design engineer to cant those end sections upwards 2 in. [50 mm] above true horizontal, from the last support. There was temporary shoring under the truss members to achieve that upward cant. After the truss was fully erected and all the field welds were made, the shoring had to be removed, and the weight of the structure had to be carried by the trusses. There was a predicted drop for the weight of the steel, and a predicted drop for the added weight of the concrete, and a predicted final drop when the wall cladding was added. So we were quite apprehensive to see if we would maintain the proper deflection. It was supposed to deflect about 2 in. [20 mm], and that's what it did. At that point, we knew we had the job in hand."

For those who built the structure, it represents a triumph of meticulous planning and precision

The Topping-Out Ceremony

On May 23, 2003, with over 3,000 people cheering him on, former President Clinton added his signature to a beam already adorned with the names of 5,000 donors to the William J. Clinton Presidential Foundation. It was the final piece of steel to be hoisted into place signifying the completion of the structural phase of the library's construction. The *Arkansas Democrat Gazette* reported that Mr. Clinton told the crowd, "I've lived a highly improbable life. I hope this library and museum will capture a little of that, but in a larger sense." Upon completion of the building, he plans to spend at least one week a month in Little Rock, living in a private apartment on the top floor, and participating in educational programs at the Clinton School of Public Service next door, which will be affiliated with the University of Arkansas.

The Clinton Presidential Center complex (Figure 5) is seen as an economic catalyst for the city of Little Rock, whose mayor, Jim Dailey, told the *Gazette* "New businesses are coming here, and the city is attracting a great deal of attention because of the library." For the engineers, foremen, ironworkers, and fabricators who built the steel structure, it represents not only hometown pride, but a triumph of meticulous planning and precision welding. As Warren Lenon, quality assurance manager for AFCO, said, "The most satisfying thing was just seeing how it welded together. It really went together well."

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Figure 4. Cap girder erection on pier.

Figure 5. The William J. Clinton Presidential Center and Park.

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Photograph courtesy of Arkansas Aerial Photography

Truss progress on the Clinton Presidential Library in Little Rock, Arkansas. *See story on page 17.*

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