Potential Gains through Welded-Wire Fabric Reinforcement

By Leonhard E. Bernold,[1] Member, ASCE, and Peter Chang[2]

Abstract: The proper placement of reinforcing steel for concrete construction requires a high degree of craftsmanship and is traditionally done by hand on the job site. Many recommendations have been published by the Concrete Reinforcing Steel Institute (CRSI) and related institutes to highlight crucial guidelines for the successful use of reinforcing bars in concrete. However, the traditional sequence for placement of steel reinforcement is the cause of many errors, omissions, and unproductive labor and equipment hours. This paper presents the results of a study that evaluates the use of welded-steel mesh (WSM), referred to as welded-wire fabric (WWF) by the American Concrete Institute (ACI), for bridge decks. Several different placement scenarios are discussed together with the potential improvements in productivity. Also addressed are the effects on quality and overall cost when using WWF instead of traditional steel reinforcing bars.

Introduction

The placing and tying of steel reinforcing bars (rebar) is one of the most labor-intensive activities on a construction site. According to Lamb (1985), some problems that can lead to errors originate from the design, such as poorly detailed shop drawings. Other errors are caused by a lack of skills, experience, and supervision on the construction site.

An alternative to traditional rebar is the use of prefabricated meshes or cages that are welded in a plant for subsequent shipment to the construction site by truck. Commonly used for reinforcing walkways, the thin welded-wire fabric (WWF) is shipped in rolls that are easily cut to size on site. The use of WWF, also called welded-steel mesh (WSM), for structural reinforcement has long been considered a standard in Europe. The German Deutsche Industrie Norm (DIN) 1045 addresses the technical details for the design of reinforced concrete using WWF. Other countries, such as Switzerland, have also established similar standards. Studies have proven the economic advantages that lead to its use not only for precasting, but also for use in sewage treatment plants, tunneling, and office buildings (Herkommer et al. 1983). German and Swiss companies are producing increasingly more sophisticated welding and bending machines to efficiently produce and use WWF for a variety of applications, such as stirrups or column reinforcement.

WWF, with wire sizes as large as ½ in. in diameter and variable spacing between the wires in either direction, have long been available in the United States. Although the use of WWF as a structural reinforcement is allowed by design codes by such organizations as ACI ("ACI" 1988) and the American Association of State Highway and Transportation Officials (AASHTO) (*Standard* 1985), engineers have avoided its use because of the lack of experience and quality control of the WWF produced in this country (Lamb

[1]Assoc. Prof., Dept. of Civ. Engrg., North Carolina State Univ., Raleigh, NC 27695.
[2]Assoc. Prof., Dept. of Civ. Engrg., Univ. of Maryland, College Park, MD 20742.

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1985). The bridge deck is one area where WWF could provide great opportunities to increase productivity and quality. The following paragraphs will present a short history of WWF and the results of a technological and economical analysis of the use of WWF for bridge decks.

Historical Background of WWF

WWF has been used as a prefabricated concrete reinforcing material since the beginning of the 20th century. In 1901, using Elihu Thomson's resistance welding, inventor John Perry, of Clinton, Massachusetts, fused continuous lengths of wire at right angles to cross wires to make wire mesh fencing. With the adaptation of this material for use as reinforcement in concrete, four types of distributed reinforcement appeared. They were (1) Rectangular welded-wire fabric; (2) rectangular staple-tie mesh; (3) triangular woven-wire mesh; (4) and expanded metal. WWF was not used in reinforced portland cement concrete until after 1910 (*Bending* 1981).

By 1915, WWF was being used in New York City as reinforcement in cinder arch concrete floor systems. By 1928, the ACI included WWF in its code as an acceptable building material. WWF was used in 1929 in the construction of the Empire State Building. Then, in 1936, the American Society for Testing and Materials (ASTM) published the first national specification.

WWF is manufactured from controlled, hot-rolled low-carbon steel rods, which are produced in a number of sizes according to the need. The rods are cleaned of mill scale and rust. They are drawn through a series of carbide tungsten steel dies at room temperature, a process that reduces the rod diameter (a process known as the cold-drawing process), and converts the rods into wires. Through the cold working of the metal, the mechanical properties are changed, increasing the stiffness, hardness, and tensile strength, while reducing the ductility of the material. A smooth, round wire of the desired diameter is the result. The wires are then used in the production of welded-wire reinforcement fabric. In case deformed WWF are produced, the wires are reshaped on rollers in the steel mill, before the wire has cooled, and after it has been completely reduced to the correct diameter.

The wire intersections are welded by electrical resistance using a continuous automatic welder. Pressure and heat fuse the intersecting wires into a homogeneous section. Epoxy-coated mats are obtained by fusion bonding of epoxy powder onto heated wires.

One development that has helped expand the use of WWF is the mesh bender. The mechanical bender is capable of shaping mesh into column ties, beam stirrups, and stair reinforcement for buildings, as well as for more complicated shapes. WWF can be bent to the exact shape of the design and dropped into a form (Ramsey 1981).

Although in 1974, the Concrete Reinforcing Steel Institute (CRSI) still referred to welded-steel mesh (WSM) as temperature reinforcement, WWF was being used extensively as structural reinforcement in Germany. During that time, the German Institute for Construction Science and Technology (Institut fuer Arbeits-und Baubetriebswissenschaften in Leonberg) did extensive studies on single- and double-reinforced concrete slabs. The results of that study were published in "Arbeitszeitwerte" (1977). The following section briefly discusses the final conclusion of that report and shows its effect on the analysis of estimating savings between the traditional and WWF reinforcement.

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Comparison of Man-Hours for WWF and Rebar Placement

The economy of using WWF is based on reducing the time required for placing and tying of rebar on construction sites. The premise is that the higher cost for prefabricated WWF is more than outweighed by the cost savings due to higher productivity during construction. The work studies done by the Institute for Construction Science and Technology on flat slabs have shown that the productivity can be increased by up to 250% "Arbeitszeitwerte" (1977). Fig. 1 shows typical placing times mentioned in the German study.

Fig. 1 presents a plot of the weight of steel in kg/m^2 versus man-hours per *t* for placement that includes (1) Unloading and storage using a crane; (2) transporting of WWF onto the formwork with a crane; and (3) placement (by hand or with crane) of WWF. For example, a typical bridge slab requires 10 kg (22 lbs) of steel per m^2 (10.9 sq ft), and the man-hours required to cover a deck of 200 m^2 (2,178 sq ft) is 440, 92, and 120 when using conventional rebar, one layer of WWF, or 2 layers of WWF, respectively. The data for these curves were collected on commercial and residential construction in the area of Stuttgart, West Germany, and it did not include work needed for additional reinforcement of corners and borders using conventional rebar. The data is based on uninterrupted work and includes 25% allowances for auxiliary time (8% for resting and 17% for personal needs).

Herkommer et al. (1983) compared the results of their study with the standard productivity rates for conventional rebar for a one-way slab. In summary, they concluded that on average the productivity increases by 15 man-hours/*t* of steel when using WWF instead of traditional rebar. For example, for the same steel density of 10 kg/m^2 (2.02 lbs/sq ft), the placement of conventional rebar has to be estimated at a rate of 22 man-hours/*t*. An overall comparison between WWF and conventional rebar shows that a man-hour savings of 1:2 in flat elements, 1:3 in columns, and 1:4 in walls can be expected.

Innovation in Design and Supports of WWF Mats

As described earlier, the use of WWF simplifies the work of placing reinforcing bars. The fact that WWF is assembled by welding intersecting

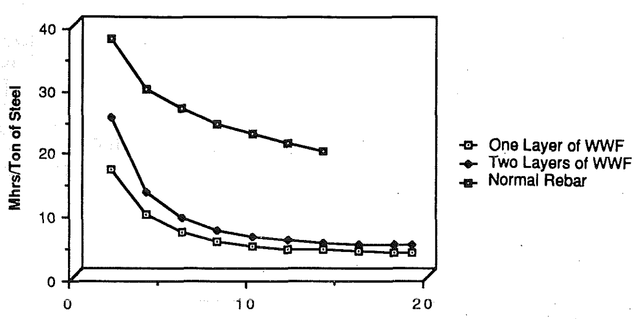

FIG. 1. Standard Laying times for WWF and Traditional Rebar ("Arbeitszeitwerte" 1977)

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bars explains why the bars are much more accurately spaced and don't move as concrete is placed. However, arranging splices for fabric mats is often more involved than for deformed bars. Because the wires are crosswise welded together, a splicing of a traditional mat configuration requires a flip-flop arrangement in order to minimize the number of wire layers. Nevertheless, the number of layers needed for splicing mats is prohibitive for use in the standard bridge-deck designs. Because of this limitation, an alternative mat design is proposed. The key element of the alternative is the elimination of the cross wires within the splice area of one of the two overlapping mats. This results in a mat shape as shown in Fig. 2 where the wires extend with splice length on two sides of the mat.

Using the WWF mats as shown in Fig. 2, the longitudinal and transverse wires stay at the same depth and the construction difficulties of splicing mats are eliminated. This is by far the best solution with respect to construction productivity and quality, and the structural design point of view.

Reinforcing steel should be accurately located in the forms and firmly held in place before and during the placement of concrete by means of supports. Steel supports must be sufficient in number and strength to properly carry the reinforcing steel they support ("ACI" 1988). Traditionally, a flat bridge deck requires two layers of steel, commonly known as top steel and bottom steel. Normally, individual and continuous chairs are used to support the two layers. The high chair, called the beam bolster upper (BBU) for beam reinforcement, supports the top-layer steel and the bottom chair, the bottom reinforcing steel. From the production point of view, the design of these chairs can have a big effect on the time spent placing the WWF. In other words, should the design of the chair require many complex handling maneuvers, the advantage of using WWF from the productivity point of view may be countered by the difficulty of chair placement.

The goal was to develop a chair that would fulfill both support functions for the top and bottom WWF layers, would increase the material and labor efficiency, and that also could be used for the prefabrication of WWF cages that require special lifting capacities for handling. The newly developed chair is shown in Fig. 3.

The chair illustrated in Fig. 3, showing a three-dimensional view in 3(*a*) and a cross section in 3(*b*), can be used to support both the lower and upper mats. The basic idea of that chair is that the chair heads fit inside the spacing of the lower mat. The upper runner provides the support for the lower mat. After the lower mats are in place, a single bar is placed in a holding groove at the head of the chair and may be tied at two points to the chair. The upper mat can then be placed on top of the chair.

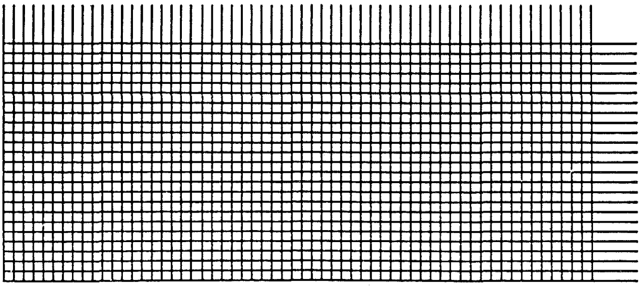

FIG. 2. Innovative WWF Configuration

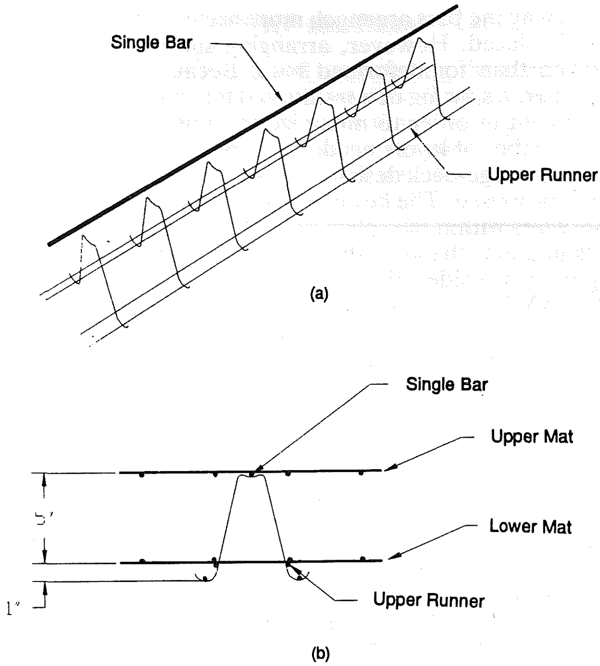

FIG. 3. Chair Design for Efficient WWF Placement

The fact that both WWF layers are supported by one and the same chair makes it a multipurpose chair that can also be used for the prefabrication of cages. The key advantage is the fact that these chairs can be used as hooks to lift the entire cage with a crane. Since both WWF layers rest on the chair, lifting the chair results in lifting both layers at once.

Improved Quality

According to Thomas Lamb (Lamb 1985), reinforcing steel placement is often not thoroughly inspected and documented on construction projects. A brief check of reinforcement steel placement is insufficient to adequately inspect and document the many important placement details. The following errors and omissions of steel reinforcement were observed in the construction industry by Lamb: (1) Improper bending of bars; (2) missing bars; (3) incomplete drawings; and (4) reversed bars.

The use of WWF in construction provides the opportunity to increase the quality of the reinforcement. Since WWF is prefabricated and welded in plants, the chance of missing a bar is virtually eliminated. The chance of improper bending of some bars is reduced by using WWF since bending machines bend the mat as a single unit. In addition, the use of WWF eliminates the change of misplacement since only one type of mat is used on a given section.

Structural Strength

Because WWF is produced by a cold-drawn process, its ductility is generally less than that of conventional steel. That is, the ultimate strain of conventional steel is generally larger than the ultimate strain of cold-drawn steel. When two simply supported slabs are tested, one reinforced with WWF and the other reinforced with conventional steel, the slab reinforced with conventional steel can be designed to deflect significantly more than the one reinforced with WWF. Since engineers often design bridge decks as one-way slabs, they reason that conventional steel is superior to WWF because the larger deflection can serve as a warning to imminent failure.

In reality, bridge decks are supported by girders; consequently they are partially restrained. These restraints may change the behavior of the slabs in two ways. First, the load-carrying capacity is increased from 20% to as much as 200% depending on the load pattern and the stiffness of the supporting girders. Second, the ultimate deflection of the slab is reduced regardless of the ductility of the reinforcement steel. These effects are generally known as the dome, or arch, effect. Therefore, if the proportions and stiffness of the system is such that the dome effect is developed, then large deformation may not be developed. Instead, safety is provided because the ultimate load-carrying capacity is much higher than the designed ultimate load (Chang et al. 1989).

Wires with welded intersections have been tested under fatigue loads at the University of Maryland (Al-Mutairi et al. 1989). Results of the experiments indicated that the fatigue strength of these wires is adequate to be used in bridge slabs. The more stringent test of moving wheel load, however, was not performed because of the lack of equipment. Slabs reinforced with conventional rebar generally failed by losing large pieces of concrete. This is believed to be caused by the propagation of small cracks from many points of the slab. In this scenario, WWF reinforced slabs would probably perform better than slabs reinforced with conventional rebar because the welded connections found in WWF provide a stiffer slab.

WWF Placement Methods

Mats can be placed either manually or mechanically. Placement methods, either manual or mechanical, are affected by, but not limited to, the following four factors: (1) Distance from the storage area to the bridge deck; (2) accessibility of the bridge deck; (3) length of the bridge deck; and (4) weight of the WWF mat used.

Manual Placement

According to a National Institute of Occupational Safety and Health (NIOSH) technical guide (*Work* 1981), the maximum allowable weights lifted with administrative controls (i.e., for which special instructions are given), lies between 55 lbs (245 N) and 160 lbs (712 N) when kept close to the body or between 30 lbs (133 N) and 100 lbs (445 N) when the object is kept 4 in. (10 cm) away from the body. The average vertical location of the object and the frequency of the lifts needed can also be considered by reducing the maximum weights. According to the NIOSH guidelines a reduction factor of 50% represents lifts that originate below 75 cm and are more or less continuous. Thus, the maximum manual lifting capacity with appropriate instructions is between 50 lbs (222 N) and 80 lbs (356 N). The NIOSH guide does not provide any limitations for carrying.

Based on observations in the construction industry, one can assume that the average steel laborer today carries 75 lbs comfortably (Allison 1991), which lies below the suggested maximum weight of 80 lbs. With the assumption of equal weight distribution, a crew of six is able to carry a mat weighing between 450 lbs (2 kN) and 480 lbs (2.13 kN). For the comparative evaluation later in the paper, a mat that weighed 384 lbs (1.7 kN) was used, which provided allowances for unequal weight distributions. Based on the German study ("Arbeitszeitwerte" 1977), the maximum distance for carrying WWF mats is assumed to be approximately 50 ft (15 m).

Mechanical Placement

The traditional method for lifting and transporting heavy material on the construction site is the use of a crane. It was found that small mobile cranes (22-t capacity) are able to place mats and cages in most situations. Different types of cranes can be used depending on the accessibility of the construction site and the size of the bridge. Should parts of the bridge not be easily accessible by crane (e.g., bridge over existing highway or river) several alternative concepts can be envisioned. A very interesting concept in placement technology is the use of the work bridge of the concrete finisher. A structural analysis has shown that, for example, the common concrete bridge finisher GOMECO 3000, with a 65-ft wide span can safely carry 3.76 kips, which is more than enough to carry a 40-ft × 8-ft cage weighing approximately 2.15 kips.

Mechanical versus Manual WWF Placement

As a means to compare the mechanical and the manual WWF placement methods, the total variable cost, which included (1) Material; (2) labor; and (3) equipment, was taken as a measure. The many possible combinations of bridge length, bridge width, mat lengths, and mat widths made it advisable to develop a computer program that was able to calculate detailed cost information for a given data set (Nez-Al Nashef 1989).

Productivity rates for manual and mechanical placement are preselected. For the manual productivity rate, an average production rate of 4.0 man-hours/*t* which, according to the German study presented in Fig. 1, relates to a steel density of 5 kg/m^2 (1 lb/ft^2). Although one might argue that the productivity in the United States might be different than in Germany, the present study still remains valid as a comparative study. For this analysis, an average mechanical productivity rate of 1.4 man-hours/*t* was selected. The cycle time of the crane includes picking up of a mat using a spreader, lifting and swinging the mat to appropriate placement location, placement, and swing back.

The program automatically switched from manual to mechanical placement if a human carrier (rodman) has to handle more than 65 lbs. This maximum load allowed for unequal load distributions encountered by different members of the team. A data base contains detailed information concerning the specifications (e.g., unit weights) of all available mat configurations. The program was designed to provide the design engineer with guidance rather than absolute numbers of calculated optimality. A typical graphical output of the program, presented in Fig. 4, shows the results of a sensitivity analysis for mat lengths between 12 and 40 ft. The following example of the input data shows the information that has to be provided by the user:

1. Minimum type of mesh to be used: D12.
2. Minimum length of mat: 12 ft.

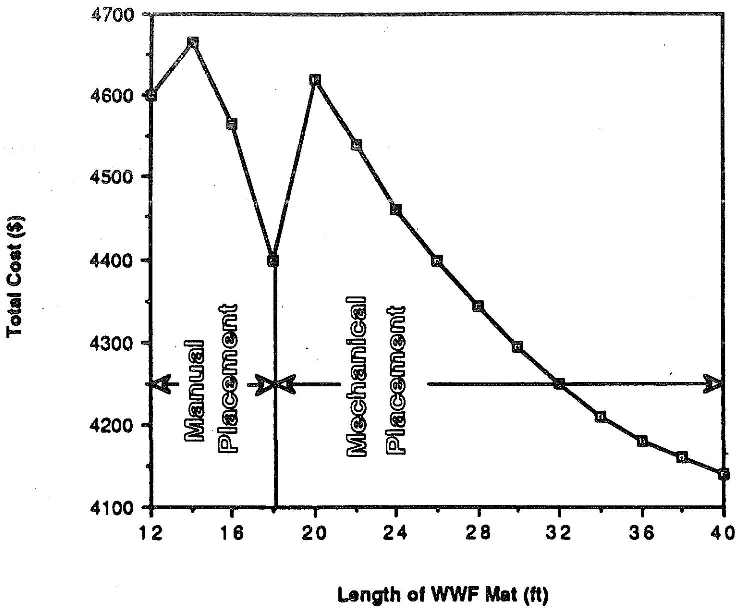

FIG. 4. Cost Sensitivity of Manual and Mechanical WWF Placement

3. Spacing of mesh longitudinal: 3 in.
4. Width of mat: 8 ft.
5. Spacing of mesh transversal: 4 in.
6. Length of slab (bridge): 100 ft.
7. Labor cost: $21.39 per hr.
8. Foreman cost: $22.60 per hr.
9. Crane operator cost: $27.49 per hr.
10. Crane cost: $144.00 per hr.
11. Overhead cost: $60.00 per hr.

The cost curve, presented in Fig. 4, covers mat sizes between 12 ft and 40 ft. The curve shows two distinctly different areas. The first includes the mat lengths between 12 and 18 ft, and the second part includes the mat lengths between 18 and 40 ft. As depicted, the jump in total cost between mat lengths of 18 and 20 ft indicates the switch from manual to mechanical placement. The mat size of 8 ft × 12 ft, which has a total weight of 230 lbs (1 kN), results in approximately 57 lbs (253 N) for each laborer, when carried by four laborers. The largest mat that can be transported manually is 8 ft × 18 ft, weighing 384 lbs (1.7 kN). For this size mat, six people are needed. Fig. 4 shows that the most cost-effective solution is to use 40-ft long mats handled with a crane. If no crane is available, 18-ft long mats should be utilized, since this results in the lowest total cost if only manual handling is possible.

The next section of this paper shows a cost comparison between the traditional reinforcement with the use of rebar and the different placement methods of WWF.

Cost Comparison of Rebar and WWF Reinforcement for Bridge Decks

For cost comparison, a slab-on-girder bridge at the intersection of Kenilworth Avenue and Greenbelt Road in Greenbelt, Maryland was selected as a reference. The dimensions of the bridge, 63 ft (19.2 m) × 230 ft (70 m) with an 8-in. (20.3-cm) slab, represent a four- (including sidewalls) lane bridge over a four-lane highway. The state of Maryland requires that 100% of the rebar connections are tied.

The following analyses are based on real and estimated values. For example, the presented cost data for the traditional rebar placement are based on estimated unit cost for labor, but on actual data for material. The productivity rate is based on actual observations on the Kenilworth bridge. The cost data for manual and mechanical placement of WWF are based on estimated unit cost for labor, consistent with the traditional rebar-placement method, and average prices for equipment provided by a local contractor in 1989. The proposed new mat configuration is being manufactured in the United States. The unit price of \$750/t, which includes epoxy coating, is a quoted price. The productivity rates for both WWF placement methods are based on estimates and will be discussed in more detail.

Table 1 summarizes the cost comparison between the traditional cost of rebar and the two methods for placing WWF reinforcement for the previ-

TABLE 1. Cost Comparison of Rebar Reinforcement and WWF Reinforcement for Kenilworth Bridge

	Placement Method		
Cost Items (1)	Traditional rebar (2)	WWF D12 manual (8 × 18 ft) (3)	WWF D12 mechanical (8 × 40 ft) (4)
Material			
Quantity (t)	45.7	44.5	43.0
Unit cost (dollars)	600.00	750.00	750.00
Total base cost (dollars)	27,420.00	33,375.00	32,250.00
Total cost including 10% O&P (dollars)	30,162.00	36,712.00	35,475.00
Labor			
Productivity (man-hours/t)	18.8	4.0	1.4
Crew			
Foreman	1 at \$22.00	1 at \$22.00	1 at \$22.00
Skilled laborers	4 at \$20.00	5 at \$20.00	2 at \$20.00
Unskilled laborers	4 at \$15.00	8 at \$15.00	2 at \$15.00
Crew cost (dollars/hr)	162.00	242.00	92.00
Total crew time (hrs)	96	13	12
Total bare installation (dollars)	15,552.00	3,146.00	1,104.00
Total labor cost including 20% O&P (\$)	18,662.00	3,775.00	1,325.00
Equipment			
Crane (for placement only)	0	0	1
Cost including operator (\$/day)	0	0	1,182.00
Total equipment cost including 20% O&P (\$)	—	—	2,128.00
Total work days (work days)	12	1 1/2	1 1/2
Total cost (\$)	48,824.00	40,487.00	38,928.00
Cost savings (%)	—	18	21

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ously described bridge. Following is a discussion of the different cost groups.

Material

For calculating the quantities of the reinforcement, only the flat portion of the bridge was considered. In other words, the extra steel for sidewalks and walls is not included. The actual amount ordered from the steel mill was 45.7 t with a unit price of \$600/t. The required amount of WWF is calculated based on following mat configuration: the mat size is 8 ft $\times$ 18 ft, and 8 ft $\times$ 40 ft for manual and mechanical placement, respectively. Based on a splice length of 12 in., the number of wires in each direction can be computed for a 4 $\times$ 3 $-$ D12 $\times$ D12 mat configuration, meaning that the longitudinal wires are D12 spaced at four in. on center, and the transverse wires are also D12, but at a spacing of three in. (D12 is the name for a wire with cross-sectional area equal to 0.12 sq in. in the conventional wire nomenclature). The weight of a D12 wire is 0.408 lbs/ft. Then the total weights of the mats are calculated as follows

$$8 \text{ ft} \times 18 \text{ ft: mat weight} = [(18 \times 22) + (8 \times 68)] \times 0.408$$

$$= 384 \text{ lbs } (174 \text{ kg}) \quad \text{(1)}$$

$$8 \text{ ft} \times 40 \text{ ft: mat weight} = [(40 \times 22) + (8 \times 159)] \times 0.408$$

$$= 877 \text{ lbs } (397 \text{ kg}) \quad \text{(2)}$$

The unit weight for the 8 ft $\times$ 18 ft mat is, therefore, 2.7 lbs/sq ft, and the unit weight for the 8 ft $\times$ 40 ft mat is 2.74 lbs/sq ft. To cover a width of 63 ft, nine mats of 8 ft mat are required if a 1-ft splice is used. The total quantity of steel used for the bridge can be calculated as follows:

$$8 \text{ ft} \times 18 \text{ ft: } 2 \times [9 \times (230 \text{ ft}/17 \text{ ft})] \times 384 \text{ lbs} = 98 \times 10^3 \text{ lbs } (44.5 \text{ t}) \quad \text{(3)}$$

$$8 \text{ ft} \times 40 \text{ ft: } 2 \times [9 \times (230 \text{ ft}/39 \text{ ft})] \times 877 \text{ lbs} = 95 \times 10^3 \text{ lbs } (43.0 \text{ t}) \quad \text{(4)}$$

Traditional rebar, which includes epoxy-coating, costs around \$600/t. The cost for the chairs are neglected in the cost comparison since an equal amount of chairs will be required, regardless of the layout option.

The width and the straight/unskewed shape of the Kenilworth bridge is an exception in that no waste has to be expected. Traditionally, the waste averages about 5%. The effect of such waste on cost will be evaluated separately.

Labor

Field observations provided the data for establishing productivity values for placing traditional rebar at the Kenilworth bridge. In comparing the actual productivity of 18.8 man-hours/*t* to standards such as the Means catalog (Means 1989), which lists higher productivity rates for this type of work, one has to realize that, on this project, the crew consisted of four rodmen (skilled laborers) and four unskilled laborers. In addition, not always the same workers were present on the job site during the duration of rebar placement. The higher productivity data in Means is based on a crew using only rodmen. The effect of an all-rodmen crew on productivity will be analyzed later in the paper.

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As shown in Table 1, the estimated hourly rate for the laborers results in an average unit cost for labor, including 20% overhead and profit, of \$21.6/man-hour for the traditional rebar, \$20.74/man-hour for manual mat placement and \$22.10/man-hour for mat placement with the support of a mechanical device. Means (1989), however, lists an average crew cost with union labor rates of \$36.70/man-hour. As will be shown, the higher union labor cost will impact the comparison considerably.

The productivity rates for the manual mat placement alternative, which uses only laborers for carrying mats, are based on the German study (see Fig. 1) and the study by Means (1989). The steel density for the double layer of WWF $4 \times 3 - D12 \times D12$ is 25 kg/m². According to Fig. 1, this would lead to an estimated 3.5 man-hours/*t*. In order to adjust the amount of auxiliary time, a rating provided by Oglesby et al. (1989) is used. Based on work sampling different construction trades over two years within a large construction firm, the amount of auxiliary or nonproductive time of ironworkers was 33%. As mentioned earlier, the German study ("Arbeitszeitwerte" 1977), used a rate of 25%, thus requiring an 8% adjustment. This consideration results in a productivity rate of 3.75 man-hours/*t*. Means (1989) uses a similar productivity rate for placing specially fabricated heavier gauges WWF mats. Using the estimated 0.64 man-hours/100 sq ft for the 8-ft × 18-ft mats, with 15% of the area for overlaps, an average of 3.7 man-hours/*t* can be calculated. Thus, the two productivity rates are, in fact, almost equal.

For the purpose of this comparison, the team for manual placement of mats is organized into two subgroups of six people, each carrying one mat at a time. One foreman and one skilled laborer are needed to supervise, direct, and place the chairs at their proper locations. Based on this work plan and the available data, a productivity of 4.0 man-hours/*t* is assumed, which includes a small productivity loss due to the bunching effect between the two crews (Halpin and Woodhead 1976). It should be pointed out that this estimate is probably still conservative, since the innovative mat design does not require flip-flopping the mats, as occurred in the German study.

The production rate for placement of large mats with the use of a crane is based on a mat size of 8 ft × 40 ft (398 kg) with an average crane cycle time of 5 min. One cycle includes the following tasks: (1) Hook the mat to the crane spreader; (2) swing the mat into location; (3) readjust the chairs if necessary; (4) unhook the mat; and (5) swing the crane hook back. A five-person team was found most effective as a crew. A foreman and two skilled workers would be responsible for proper placement of the mats and chairs. Two unskilled workers are needed to hook the individual mats to the crane, using a spreader beam with several hooks. The time of 5 min for one cycle is based on Means (1989) which uses an average cycle time of 3.3 min for placing concrete on an elevated slab with crane and bucket. A safety factor of 50% was used. This factor should also account for adjustments due to longer durations for hooking up the mat to the spreader beam and advancements of the track-type crane along the bridge. An experienced estimator of bridge construction projects considered it a very conservative estimate (Steve M. Allison, personal communication, March 27, 1992). In addition, the effective operational hour was considered to be 45 min (25% auxiliary time). These estimates result in a production rate of 1.4 man-hours/*t*. It has to be stressed that the situation of a bridge has to be considered when evaluating the different methods. In particular, to allow for efficient use of mechanical equipment, good access to the bridge from the side or from the ends is necessary, in order for the crane to reach the entire area of the bridge. The Kenilworth bridge, for example, allowed an easy positioning of the crane on either side of the bridge with no obstacles for repositioning the crane very speedily.

Equipment Cost

While the traditional rebar and the manual mat placement do not require any special equipment, the mechanical placement depends on cranes. It was found that most mobile cranes would be able to handle the weight of one mat. For the purpose of this analysis, a 35-T mobile crane that would position itself alongside the bridge was selected. At least one repositioning from one end of the bridge to the other, which could be accomplished during a break, would be necessary. The cost of $1,182/day shown in Table 1, which includes the crane operator, is based on a catalog price from a local crane-rental company.

Indirect Cost

For materials, a rate of 10% was added to include overhead and profit. For labor and equipment, a rate of 20% was used. These are common figures suggested by Means (1989).

Summary and Cost Sensitivity

Table 1 shows that the expected savings in the placement durations and the overall cost are significant. The cost for the traditional method of reinforcement for the Kenilworth bridge was calculated to be $48,824, based on average bare cost rates for labor and the unit cost of material. Productivity rates were based on observations. Since the actual unit cost for labor could not be obtained from the contractor, estimated values, which were again based on Means (1989), were used. Both manual and mechanical placement of WWF are based on estimated productivity, since no observation of these methods was possible. Using the same unit cost for labor, both the manual and the mechanical placement methods resulted in cost savings for the Kenilworth bridge, which amounted to 18% for the manual and 21% for the mechanically supported placement. The mechanical placement method could become even more favorable if the bridge were larger, since it takes only 1½ days for the actual placement, but the crane has to be rented for two full days.

Perhaps the most dramatic effect of WWF placement over the traditional approach is the time savings. While it traditionally takes approximately 2½ weeks to place the reinforcement for the Kenilworth bridge deck, the use of WWF is estimated to allow the bridge to be reinforced within 1½ days.

As discussed earlier, a change in productivity and unit cost for labor as well as the consideration of situations not encountered on the selected Kenilworth bridge may impact the outcome of the cost comparison. Table 2 shows the results of changing the cost rate for labor as well as adjusting the observed labor productivity. Separately, the consequences of adding 5% material waste for reinforcement with WWF is presented. The increase in labor cost rate to $36.7/man-hours, as discussed earlier, is assumed to be accompanied by an increase in productivity. Based on Means (1989), the average rate for placing traditional rebar on elevated slabs is between 9 man-hours/ton (9.9 man-hours/*t*) and 14 man-hours/ton (15.4 man-hours/*t*). In order to account for the 100% ties required for the bridge deck, the upper limit is being chosen for the following analysis.

As shown in Table 2, the comparison of overall cost is sensitive to changes

TABLE 2. Effects of Higher Labor Cost and Material Waste

	Placement Method		
Cost Items (1)	Traditional rebar (2)	WWF D12 manual (8 × 18 ft) (3)	WWF D12 mechanical (8 × 40 ft) (4)
Material			
Original total cost including 10% O&P ($)	30,162.00	36,712.00	35,475.00
5% waste for WWF	—	1,836.00	1,774.00
Adjusted total cost including 10% O&P ($)	30,612.00	38,548.00	37,249.00
Labor			
Original average crew cost ($/mhr)	21.60	20.74	22.10
Original total labor cost including 20% O&P ($)	18,662.00	3,775.00	1,325.00
Adjusted average crew cost ($/mhr)	36.70	36.70	36.70
Adjusted labor productivity (mhrs/t)	15.40	—	—
Adjusted total labor cost including 20% O&P ($)	25,829.00	6,679.40	2,202.00
Equipment			
Total equipment cost including 20% O&P ($)	—	—	2,128.00
Total cost			
Original total cost ($)	48,824.00	40,487.00	38,928.00
Total cost with 5% WWF waste ($)	48,824.00	42,323.00	40,702.00
Total cost with Adjusted labor rates ($)	55,991.00	43,391.40	39,805.00
Total cost with combined effect ($)	55,991.00	45,227.40	41,579.00
Cost savings			
Original cost savings (%)	—	18%	21%
Savings with 5% WWF waste (%)	—	13%	17%
Savings with Adjusted labor rates (%)	—	23%	29%
Savings with combined effect (%)	—	19%	26%

in labor and material cost. Estimated cost savings with the adjusted crew cost and improved labor productivity are 23% and 29% for the manual and the mechanical methods, respectively. Cost for 5% material waste of WWF has an obvious negative effect on estimated cost savings, which were reduced by 4–5%. Combining these two changes ended up favoring the mechanical method more (26% cost savings) than the manual placement method (19% cost savings).

Conclusions

This paper presented a feasibility study and cost evaluation of welded-wire fabric (WWF) as the primary reinforcement of bridge decks. The technological, operational, and economical aspects of the use of WWF for this purpose have been investigated.

A detailed report produced in Germany ("Arbeitszeitwerte" 1977) provided scientific data on savings in using WWF in construction. The presented study investigated further possible productivity improvements through changing the design of the mats and the supports. Additionally, mechanical and manual placement methods were compared. Also addressed is the structural strength of the WWF reinforcement.

It was demonstrated that this reinforcement concept provides many opportunities for innovation in the use of WWF, as well as the efficient placement of the mats. A cost comparison between the traditional rebar reinforcement and the WWF, using an actual bridge in Greenbelt, Maryland, suggests that significant savings in time and cost may be possible.

It is felt that WWF is a technology that may be ready for wider use in the construction industry. Prefabrication makes WWF a more expensive material than traditional rebar, but will help to reduce the laborious work on site.

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