Application of Robotics in Bridge Deck Fabrication

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Abstract: Application of robotics in welding orthotropic steel decks for bridges is investigated. It is found that by using robot welders, savings of about 5.6% can be realized in the fabrication cost of the steel decks. Deterioration of the bridges' concrete decks at alarming rates has bridge engineers looking at alternative systems. Orthotropic steel decks are particularly attractive because they last longer than concrete, reduce the bridge's dead load and can be replaced without major disruption of traffic. Traditional methods of steel deck fabrication are costly and labor intensive. Based upon the findings of the research described in this paper, if robotics technology is used in steel deck fabrication, the required man-hours and the fabrication costs may be reduced. This would reduce the initial cost of steel decks making them competitive with the cost of concrete decks. Considering life cycle analysis, orthotropic steel decks appear to be even more competitive with the concrete decks. In this investigation, a typical orthotropic deck module was designed using approximate methods. Several steel fabricators were contacted and price quotations for fabricating this module were obtained. A model of a robotics system for welding of this deck module was conceived, the robot's specifications prepared and the cost of the system estimated. A comparison of the cost of the conventional and robotic fabrication and analysis of results are presented.

Introduction

In the recent past, three bridge deck repair projects in various parts of the country have used steel decks to replace deteriorated concrete decks. In all three cases—the Golden Gate Bridge in San Francisco, the Ben Franklin Bridge in Philadelphia, and the Throgs Neck Bridge in New York—the primary motivation was the same: to lower life cycle cost; to increase the loading capacity; and to make repairs quickly with minimum disturbance to the traveling public.

The repair and replacement of deteriorated concrete bridge decks is one of the major problems facing bridge engineers, particularly in the northern parts of the country (Wolchuk 1986, 1987). According to one estimate, bridge deck replacement results in expenditure of 1–2 billion dollars per year in the United States (Maser 1987). The bridge deck is the most severely stressed structural element of a bridge due to its direct contact with heavy cyclic loading from traffic and to its exposure to adverse weather effects. Cyclic loading results in alternating stresses in the deck causing material fatigue and cracking in concrete. The design loads stipulated by the American Association of State Highway and Transportation Officials (AASHTO) and used in most bridge deck designs are frequently surpassed by heavy trucks. Such loading results in overstressing of structural components of the bridge (Wolchuk 1987). Bridge authority officials are experiencing difficulties in restricting illegal loads from passing over their bridges even with vigorous

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enforcement of the loading limit. Apparently, drivers of heavy vehicles can usually find ways to bypass the check points (Moses 1987). According to Moses (1987), more than 200,000 of the nation's 600,000 bridges are listed as deficient with the current remedial cost stated as over $50 billion. Another factor limiting the useful life of a concrete deck is the action of deicing salts that penetrate the concrete, causing the reinforcing steel to corrode and the bottom of the deck to spall. Cracks that develop in the concrete facilitate the penetration of deicing salts and accelerate deck deterioration. This in turn results in high maintenance and remedial construction activities with disruption to traffic.

Steel Decks

With very daring, long span concrete bridges being constructed and with similar older bridges in Europe now experiencing difficulties, it would be wise to encourage the development of competing systems in steel. Existing steel decks have been exposed to similar loading conditions, adverse weather fluctuations, and deicing salts. Two such bridges in the northeastern part of the country were inspected in 1964 and found to be in good condition with only insignificant corrosion damage after 27 years of service (Wolchuk 1964 and 1987). These bridge decks are still functioning well today after 50 years of service in environments that limit concrete decks to a life span of 20–30 years (Envirodyne-Lichtenstein 1980).

The use of steel plate bridge decks has not been pursued by the steel fabrication industry because the cost of production in the traditional fabrication shop has been high. Currently steel decks do not compare favorably in initial costs to concrete decks. Since fabrication costs are high the steel deck market remains small. With a small market, investment in new production techniques are not justified to reduce costs. A research was conducted to break this cycle by determining whether manufacturing steel plate decks using robotic welders will reduce the in-place cost of a steel deck system sufficiently to be a competitive alternative to replacement decks of concrete. This paper describes the findings of this research effort.

The research has focused on orthotropic steel decks. An orthotropic steel deck module was designed and used as a comparison model of a typical steel deck in this work. The fabrication cost of the typical steel module using conventional and robotic methods were compared to quantify the cost savings in deck fabrication due to robot utilization.

Several sensitivity analyses were performed to investigate the effect of different factors (e.g., interest rate, labor wage rate, robot utilization rate, etc.) on the economics of the robot welder in the fabrication process. Based upon the findings of this research, robotization, not only of the welding operation discussed in this paper, but of other fabrication steps (e.g., handling, cutting, assembly, testing, coating), would increase productivity and cause considerable cost savings. This will make the orthotropic steel decks very competitive with concrete decks at the initial cost level. Taking life-cycle economic factors into consideration, the orthotropic steel decks appear to be even more competitive with the poured-in-place concrete decks.

BACKGROUND

Problems with concrete decks have triggered research efforts to investigate alternative decking systems. Grid-reinforced concrete decks, exodermic bridge grid decking, open-steel grid bridge flooring, and orthotropic steel decks are being studied and evaluated (Gilmore 1987). This study will concentrate on orthotropic steel decks.

Orthotropic Steel Decks

An orthotropic deck is a hybrid name for a stiffened plate deck. The term orthotropic came about from the use of orthogonal shaped stiffeners and anisotropic properties that develop in a composite deck section. Orthotropic steel decks have been used extensively in Germany and especially in Japan in the past decades. There are several structural advantages in using orthotropic decking system. As the main objective of this paper is to investigate the application of robotics in steel deck construction, the major advantages of orthotropic decks are only briefly mentioned along with a brief description of recent redecking projects.

One of the first major redecking projects in United States using orthotropic decks dates back to only one decade. Deterioration of the concrete upper deck of George Washington Bridge in New York made the Port Authority of New York and New Jersey study different deck replacement alternatives. Their studies resulted in selection of orthotropic steel deck (Monti et al. 1980; Fasullo and Hahn 1977). Redecking of 434,000 sq ft (40,400 m^2) of the upper deck and the New York Approach ramp was completed in 1978 (Wolchuk 1987).

Golden Gate Bridge was redecked with orthotropic decks in 1984–1985. Again the concrete deterioration had reached unacceptable levels. In Amman and Whitney's conceptual report, Stahl and Custen (1980) (the engineers for this project) considered three alternatives for deck replacement: precast lightweight concrete, concrete-filled steel grating and steel orthotropic deck. Orthotropic steel deck was selected because (1) It was lighter in weight, thus reducing the main cable and suspender rope stresses; (2) it had a longer life span; (3) it had much fewer roadway joints resulting in better ride and less maintenance; and (4) it had lower painting costs. Although the initial cost of the orthotropic deck was estimated to be 6% higher than the least expensive alternative, cost savings of more than $4,000,000 in maintenance plus the cost of replacing the concrete deck could be realized over a period of 50 years (Mohn et al. 1980).

Throgs Neck Bridge in New York (Forsyth and Stahl 1963) and Ben Franklin Bridge in Philadelphia (Lazorko 1986; Wolchuk 1986) have recently been redecked by orthotropic panels. A very important aspect of the redecking operation in all of these projects was their minimum disruption of traffic. On most of these occasions, all redecking work was done at night with all lanes open to traffic during daytime.

The main disadvantage of orthotropic decks is their relatively high initial cost. As mentioned earlier, in an estimate for the Golden Gate Bridge project the orthotropic deck was 6% more expensive than the least expensive alternative (Mohn et al. 1980). The cost of orthotropic redecking for the Ben Franklin Bridge project ($56,000,000) was about $10,000,000 more than the cost of concrete decking (Lazorko 1986). This shows an initial cost difference of more than 15%. Most federal agencies choose projects based on the minimum initial cost. This will generally result in choosing a poured-in-place concrete deck over a steel deck. A life cycle economics analysis needs to be performed in order to show the true advantages of alternative systems.

However, in the writers' belief, there is a very good chance to reduce the cost of steel deck fabrication using robotics. This could make steel decks competitive with concrete decks at their initial cost.

Scope of Study

The objective of this research was to investigate the potential for robot application in the fabrication phase of an orthotropic steel deck. It was thought that the welding function, being labor intensive, would be a good area to reduce costs. In addition, robotic applications in steel welding is rather widespread. Therefore, an estimate of the capital and operating costs of a robot system for welding the deck module can be performed with a minimal amount of speculation and with reasonable accuracy.

Robotics Applications in Industry

The application of robots are far more widespread in the manufacturing and electronics industries than the construction industry. According to Warszawski (1984), about 30,000 robots were employed in various countries around the world in 1984. Most of these robots were employed in welding, palletizing, machine tool processing, paint spraying, casting and forging, loading and unloading, and inspection. More information is available about these applications in Ayres and Miller (1983), Hunt (1983), Paulson (1985), and Skibniewski (1986). The application of robotics in construction has been much less prevalent because of various social and technical difficulties (Warszawski 1984; Paulson 1985). The declining productivity in construction (Stokes 1981; Cremens 1981; "Productivity in Civil Engineering and Construction" 1983) and overseas competition have caused a great deal of concern in United States. At this time, some agencies, including the National Science Foundation, are sponsoring research in the field of construction robotics and automation believing that implementation of robotics and automation in construction operations may improve productivity (Construction Automation Research 1986; Wilson 1987).

The field of robot welding is rather mature compared to other robotics applications. In this research, welding robots have been considered only in the fabrication process. Numerous manufacturers are using robot welders in their plants for several years now. These robot welders have caused an increase in productivity, quality, and safety and have reduced labor costs. Because of the widespread utilization of robot welders, it was possible to conceive a complete robot welding system capable of welding a typical orthotropic steel deck module.

Research Methodology

The following steps were taken to investigate the economic feasibility of robot applications in deck fabrication.

1. An orthotropic steel deck module was designed [American Institute of Steel Construction (AISC) 1963] that could be used as a basis for obtaining quantities and cost information. As the main objective of research was to compare the cost of fabricating a typical deck module by conventional methods with fabrication cost of a robot welded deck, the amount of time spent on design was minimized.

Therefore, the module was designed using approximate methods. The orthotropic module is a closed-rib deck, 8 ft × 40 ft (2.44 m × 12.2 m), with trapezoidal ribs (reported by Ladick 1986).

2. AISC provided the names of several steel fabricators that were contacted to participate in the study. A drawing of the designed deck module, a specifications list, and a detailed estimate sheet were sent to steel fabricators across the country for pricing and comments. Five fabricators responded by filling out the estimate survey sheet. The estimate sheets received from the fabricators have not been included in this work for reasons of confidentiality.

3. The same estimating package was also presented to ESAB, an international welding robotics company for robot selection and pricing. Writers worked closely with the company's engineers and planners to develop a suitable system capable of welding the orthotropic deck module. A videotape of the proposed system was developed to show the various capabilities of the welding robot and a proposal was prepared by ESAB that contained all the cost details of the suggested robotic system. Using this information, the robot's cycle times and production rates were estimated.

4. An economic analysis was conducted to compare the costs of the two fabrication procedures. Several sensitivity analyses were performed to investigate the effect of different factors on the fabrication costs.

Data Collection

It was essential to know how the different functions and costs within a fabrication process were distributed. The number of actual welding manhours that would go into welding one module was also needed. This information was obtained by surveying a number of steel fabricators as previously explained in step 2. The results obtained from the estimate survey sheets were separated into four areas:

- Welding man-hours per module.
- All remaining man-hours per module.
- Cost of welding consumables.
- All remaining material costs.

The study did not consider the cost of miscellaneous steel that would be required to make the necessary connections in the field. It was thought that the inclusion of these details in the survey would complicate the estimators' task while adding little reliable data to the study. Each of the four areas mentioned above are shown in Table 1 along with their average values. These values are arithmatic averages of the bid prices received from the steel fabricators and were used to calculate the average fabrication cost per module as shown in Fig. 1. They were also used as fixed input values for the robot investment cash flow analysis (Tables 2 and 3). The average welding and remaining manhours values were multiplied by the assumed wage rate to obtain total direct and indirect labor costs. These labor costs were added to the total material cost to obtain the average conventional fabrication cost per module. The breakdown of the conventional fabrication costs of this closed-rib orthotropic deck module is presented in Fig. 1 and Table 4.

With the average nonrobotic welding manhours per module known the

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TABLE 1. Estimate Survey Values for Base Deck Module

Estimate survey sheets (randomly located[a]) (1)	Welding time per module (man-hours) (2)	Remaining labor req. per module (man-hours) (3)	Cost of welding consumables/ module ($) (4)	Cost of remaining material/ module ($) (5)	Wage rate including overhead and profit ($/hr) (6)
A	27	127.6	66	2,178	40.69
B	24	107	54	2,473	36.81
C	28.2	103.25	72	2,525	24.00
D	16	77	—	2,780	32.70
E	37	77.3	36	2,208	25.00
Average values	26.4	98.4	57	2,433	31.84

[a]For confidentiality, the values placed in rows A–E are mixed to avoid revealing a fabricator's estimate.

Note: Average values used to determine cost of fabrication.

next step was to determine the capital cost, annual costs and cycle times of a welding robot operation. A comparison between the two methods (traditional versus robotic) could then be drawn.

The ESAB Robotic Welding Division, based in Fort Collins, Colorado, provided technical assistance in selecting a robotized welding system, as well as providing estimates of capital costs and production cycle times. In order to eliminate any bias regarding the robot maintenance costs, efficiency rate and operating expenses, three manufacturing companies using similar robots were contacted (Artco-Bell, Inc., Texas; Cascade Corp., Oregon; Walker Manufacturing, Indiana). The maintenance, operating costs and efficiency rate used in this analysis were all conservatively estimated in comparison

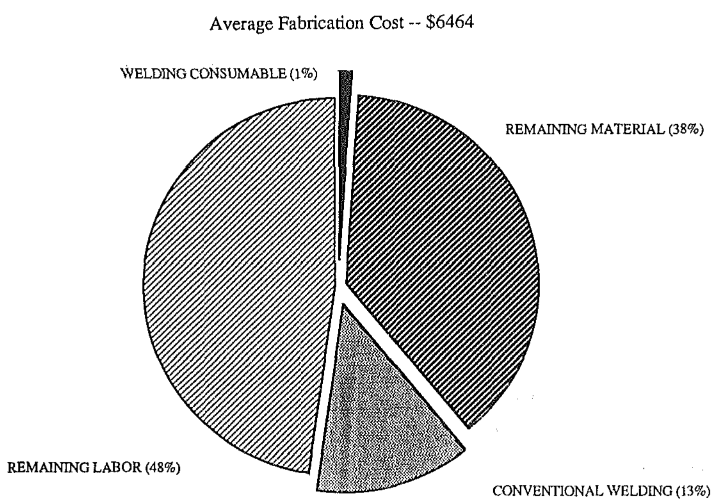

FIG. 1. Conventional Fabrication Cost Breakdown

TABLE 2. Cash Flow Table for Robot Investment[a]

Cost items (1)	Year 0 (2)	Year 1 (3)	Net (4)	Year 2 (5)	Net (6)	Year 3 (7)	Net (8)	Year 4 (9)	Net (10)	Year 5 (11)	Net (12)
Initial investment/robot	−300,000										
Initial investment/tooling	−100,000										
Start-up expense		−40,000									
Start-up expense tax saving—		19,200									
net start-up cost			−20,800								
Depreciation		160,000		96,000		57,600		34,560		51,840	
Depreciation tax benefit			76,800		46,080		27,648		16,589		24,883
Wage expense		−191,040		−202,502		−214,653		−227,532		−241,184	
Wage expense tax savings—		91,699		97,201		103,033		109,215		115,768	
net wage cost			−99,341		−105,301		−111,619		−118,316		−125,415
Maintenance of robot		−3,000		−8,000		−8,480		−8,989		−9,528	
Maintenance expense tax savings—		1,440		3,840		4,070		4,315		4,574	
net maintenance cost			−1,560		−4,160		−4,410		−4,674		−4,955
Program and operating expense		−10,000		−10,600		−11,236		−11,910		−12,625	
Program and operating expense		4,800		5,088		5,393		5,717		6,060	
tax savings—net program and operating expense			−5,200		−5,512		−5,843		−6,193		−6,565
Material expense		−38,019		−40,300		−42,718		−45,281		−47,998	
Material expense tax saving—		18,249		19,344		20,505		21,735		23,039	
net material cost			−19,770		−20,956		−22,213		−23,546		−24,959
Subtotal	−400,000		−69,871		−89,849		−116,437		−136,141		−137,011

[a]*Total present worth value* = −770,756; *robot charge-out rate ($/hr assuming 6% inflation)* = 46.50; *robot charge-out rate ($/hr, before tax)* = 89.42.

Note: Input parameters are: Labor rate = \$31.84/hr; robot investment cost = \$300,000 (includes delivery); tooling investment cost = \$100,000 (includes delivery); start-up costs = \$40,000 (includes testing); maintenance of robot = \$3,000 first year, \$8,000/year later on; operating/programming expense = \$10,000/year; material costs = \$57.00/module; inflation rate = 6%; hours/year = 4,000; crew size = 1.5 persons; tax rate = 48%; interest rate = 13%; robot useful life = 5 years; and robot efficiency = 75%. Calculations are: labor costs = \$191,040/year; number of modules = 667/year; and material costs = \$38,019.

TABLE 3. Wage Saving Calculation

Item description (1)	Computations (2)
Traditional welding time per module	26.4 man-hours/module (Table 1)
Robot welding time per module (at 75% efficiency)	9.0 man-hours/module
Welding man-hours saved	17.4 man-hours/module
Modules fabricated per year (at 100% robot utilization rate)	667 modules
Welding man-hours saved per year	11,606 hours
Labor rate (including OH and profit)	$31.84/hour (Table 1)
Wage savings generated	$369,535 per year
Number of replaced workers (assuming two shifts per day)	2.9 per shift

with the same values obtained from these companies.

The robotic system selected was made up of the following components [detailed robot system specifications can be found in the report submitted to the National Science Foundation (1988)]:

- IRb G6 Industrial Type robot with five degrees of freedom, 22k RAM, and teach pendent.
- LAH 500 R Welding Head with a 500-amp Thyristor-controlled Rectifier with an integral tactile sensing system called SmarTac. The SmarTac is capable of three-dimensional searches. The welding head is capable of automatic adjustments if the structural piece moves from its programmed location.
- Mec 44 R Automatic Wire Feeder used in the GMAC welding process.
- Raised track and boom system used to move robot over the work piece. One module requires approximately 50 robot carriage movements.
- Integrated tooling system and positioning tables capable of handling two deck modules. The tooling and tables will be used for fixturing the structural steel pieces, initial manual tack welding, and final weld-up.
- ESAB spatter cleaner to minimize robot downtime for weld head cleaning.

The production operation and facility layout is shown graphically in Fig. 2. The production operation was designed to allow module number one to

TABLE 4. Breakdown of Conventional Fabrication Costs

Costs (1)	Amount (in dollars) (2)
Conventional welding costs (26.4 hours at $31.84/hour)	841
Remaining labor cost (98.4 hours at $31.84/hour)	3,133
Welding consumables cost	57
Remaining material cost	2,433
Total	6,464

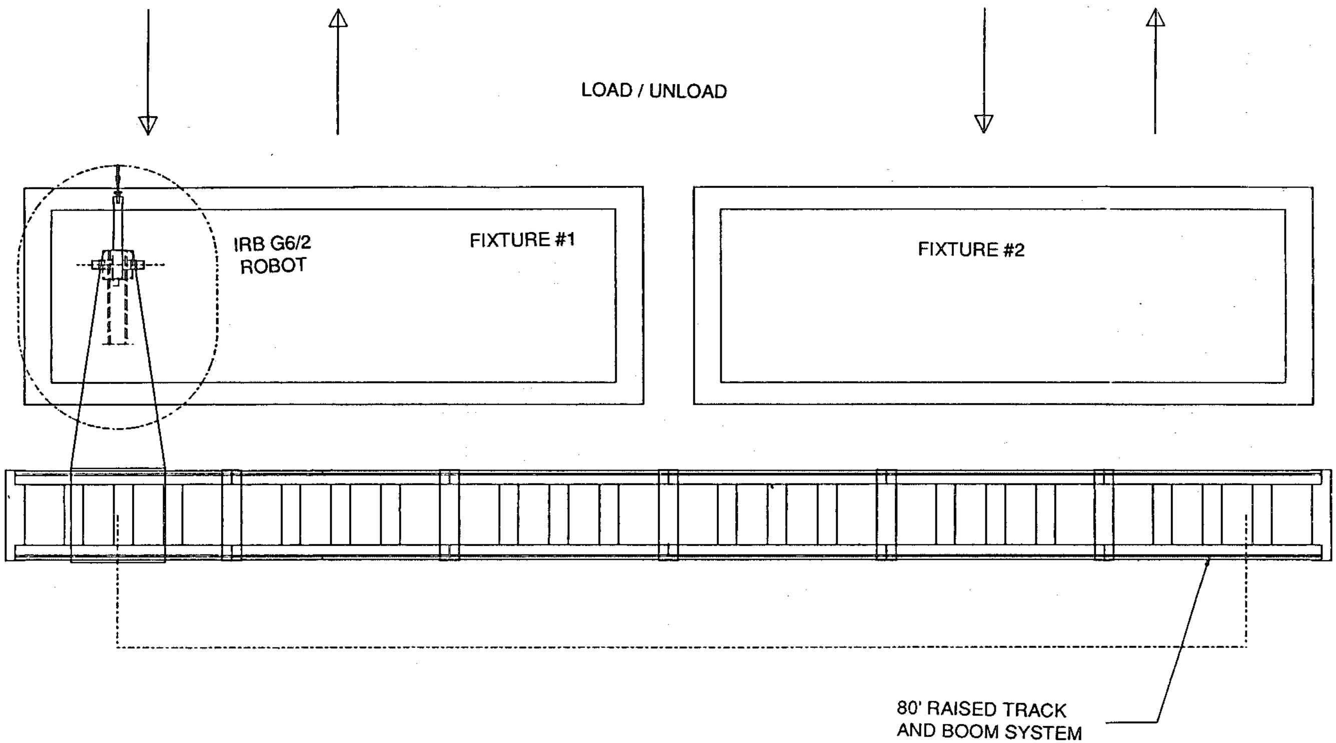

FIG. 2. Proposed Robot Welder Production Layout (Used by Permission of ESAB North America, Inc.)

be welded while the adjacent positioning table was loaded with the component pieces of module number two for tack welding. The robot operation occupies approximately 2,000 sq ft (185 m^2) of floor space. The capital cost of the robot system, excluding the positioning table and tooling, was quoted at $298,050. This included all the items mentioned above in addition to operator training and installation supervision except the space cost. The positioning table and tooling were estimated at $100,000. Robot programming and operating expense was estimated conservatively at $10,000 per year.

A research was conducted to estimate robot maintenance costs. ESAB analyzed the maintenance costs of IRB G6 Robots of about 25 customers. The average maintenance cost per robot was $3,000 for the first year and $7,000 annually for the following years. The writers directly contacted two ESAB clients that were using IRB L6 (very similar to IRB G6) Robots. Cascade Corp., the manufacturer of forklift attachments in Portland, Oregon, provided the actual maintenance cost for 1987. It amounted to about $15,000 for two IRB L6 Robots. Robots were purchased three years ago. Artco-Bell, Inc., that manufactures school furniture in Texas, has been using similar robots for the past four years. Based on the information provided by the plant manager, the maintenance costs have been approximately $3,000 per year per robot. Robots were working at least two shifts per day. In conclusion, robot's maintenance cost was estimated at $3,000 for the first year (mostly because of manufacturer's warranties) and $8,000 per year for the next years.

Welding cycle times were estimated using the following approach: Continuous welds were used at the deck to rib, and floorbeam to deck and rib connections. Completing the 5,556 in. (14,112 cm) of welds required 302 welds, 302 two-dimensional searches, and no stored start positions. An automated sensing system called Weld Guide was used along with the SmarTac. With this equipment searching will only be required at the beginning of each weld. Each of the 302 welds should be program-welded to minimize heat build up so as to reduce the chance of stress cracking and minimize warping. The welding cycle time for this option was approximately 4.5 hours at 100% utilization. The cycle times stated here do not include an operational efficiency factor. In the analysis, an efficiency factor of 75% was used to account for robot downtime, maintenance and reprogramming. This efficiency factor is a conservative estimate and is about 5–10% lower than the efficiency factor recommended by ESAB based on their past experience and historical data. Data acquired independently from two manufacturing companies using similar robots put robots' operational efficiency at more than 90%. The robot welder provides increased benefits over the conventional welding approaches when considering skip welding due to its ability to move quickly between weld points (arc cut time). Skip welding with conventional welding systems will actually increase cycle times above those required for continuous welds. Therefore, the robot welder can generate cost savings by both a reduction in welding cycle time and in expended consumables. In this study, however, skip welding was not considered because according to experts on bridge design, such welds have poor fatigue resistance, and, also, do not provide airtight enclosure of the rib interiors needed for corrosion protection.

To summarize, the 4.5-hour welding cycle time was modified to 6.0 hours by considering an operational efficiency factor of 75%. Based on the industry standards, a one-and-one-half persons crew to operate the robot work station was assumed.

Data Analysis

A number of assumptions were made in data analysis as follows.

Fabrication versus Erection Costs

Once the factors affecting the fabrication process for both conventional and robot systems were quantified, it was necessary to determine: the in-place cost of the module, the percentage of the cost attributable to the fabrication process, and the percentage attributable to the erection process. To obtain this data several sources were used. First, the bid tables from the Golden Gate, Ben Franklin, and Throgs Neck Bridges were compared. Since each of these bridges used a different type of deck system, and many of the bid figures were skewed because of bid loading, only the relative differences in percentages between one type of deck system to another could be determined. The open rib deck system required approximately five to ten percent higher fabrication costs relative to the closed deck system. This is probably because of the additional welding required on the stiffeners in an open rib system during fabrication and to the easier splice connections during erection. A few of the erection contractors were contacted in order to obtain a more reliable breakdown between fabrication and erection costs. The information received placed the fabrication cost of the open rib system between 55 and 70% and the fabrication cost of the closed rib system between 50 and 65% of the total fabrication and erection costs. Research conducted by Wolchuk (1987), placed the fabrication cost of the open rib system for the Ben Franklin Bridge at 56% and the fabrication cost of the closed rib system for the Throgs Neck Bridge at 53% of the total costs. The steel deck modules for both these projects were fabricated in New York and shipped to location. Based on this discussion, the authors elected to use a fabrication cost of 55% and an erection cost of 45%. These values were used in analyzing the costs associated with the basic closed rib deck system considered in this study.

Depreciation Considerations

The Internal Revenue Service was contacted to ascertain the method of depreciation to be used in costing the robot system. *IRS Publication 534* (1986) states that all tangible property placed in service after 1986 shall be depreciated by the modified accelerated cost recovery system (MACRS). The recovery period for the robot system is defined as a five year property based on a class life between four and ten years. The depreciation method for a five year property is the double (200%) declining balance with salvage treated as zero. The new tax law no longer provides an incentive tax credit to industry for investing in capital expenditures. Informal discussion with IRS personnel indicated that such incentives will be a part of the 1988 tax bill; for this study the writers were unable to take advantage of any tax credits.

Cost Analysis

To draw an economic comparison between the traditional welding process and one augmented with the robotic welding operation it was necessary to determine the robot charge-out rate and the robot welding cost per module.

Robot Investment Calculations

To determine the robot charge-out rate a cash flow analysis was performed on the robot welding operation using a Lotus 1-2-3 spreadsheet (Tables 2 and 3). Many of the input parameters listed were covered earlier in this paper. The wage rate used in the analysis was \$31.84/hr. This value represents an average wage plus overhead and profit based on the rates received from the five fabricators who participated in the study (Table 1). Material cost (\$57 per module) was assumed to be equal to the average material cost in a continuously welded deck (Table 1). The cash flow table represents the yearly cost of ownership and operation. The present worth of the total costs over the five-year period was calculated to be \$770,756. The after-tax robot charge-out rate of \$46.50 was determined by converting the present cost of ownership and operation (\$770,756) to a uniform series on an annual basis. Also the charge-out was inflated in each period to reflect the 6% inflation rate used in the analysis. Before-tax charge-out rate was then calculated as \$89.42/hour assuming a 48% tax rate. The robotic welding cost per module was calculated at \$536.50 by multiplying the charge-out rate by the number of hours required to weld one module (six hours). Welding cost of one module using conventional approach was calculated as the sum of labor and material costs as received from the steel fabricators. This amounts to \$841 + \$57 = \$898 (Fig. 1).

With these costs identified, a reduction of 5.6% in the fabrication cost resulted from the use of robotics in the welding operation as compared to conventional approach. The percent reduction in the fabrication cost (5.6%) was calculated by dividing the cost saving between robot and manual welding (\$898 − \$536.50 = \$361.50) by the total module fabrication cost of \$6,464 (Fig. 1). The percent reduction of in-place cost (3.1%) was calculated by multiplying the percent reduction in fabrication (5.6%) by the overall percentage fabrication cost (55%) of the in-place cost of the module.

Rate of Return Calculation

The economic justification of replacing the conventional welding fabrication method with one of robotics was examined by return on investment analysis (Grant et al. 1982; Ostwald 1984). The rate of return (ROR) was calculated at 52.8% (Table 5). The input values and assumptions in developing the ROR table such as labor rate, tax rate, inflation rate, etc. were all the same as those used in the cash flow analysis (Table 2).

The first analysis (Table 2) did not directly consider wage savings that would be generated from the robot welding operation. In the robot investment cash flow table we were concerned only with the cost of labor, equipment and material required to robotically weld the module. Considering certain assumptions, the robot operation will result in a crew reduction of 2.9 men per shift (Table 3).

Although considerable savings could be quantified for reduction in rework and scrap, energy usage and accident claims, the only saving considered in the analysis was labor reduction. Robot utilization generally results in end products with more consistent quality. In labor-intensive tasks, the quality of products vary due to learning curve effects, boredom and exhaustion. The writers have contacted several manufacturers that use robot welders. All of the managers contacted believed that using robot welders resulted in cleaner work and savings in rework and scrap. They also believed that by reducing

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TABLE 5. Rate of Return Analysis[a]

Expenditures and savings (1)	Year 0 (2)	Year 1 (3)	Net (4)	Year 2 (5)	Net (6)	Year 3 (7)	Net (8)	Year 4 (9)	Net (10)	Year 5 (11)	Net (12)
Initial robot investment	−300,000										
Initial investment/tooling	−100,000										
Start-up expense		−40,000									
Start-up expense tax saving—		19,200									
net start-up cost			−20,800								
Depreciation		160,000		96,000		57,670		34,560		51,840	
Depreciation tax benefit			76,800		46,080		27,648		16,589		24,883
Wage savings—replaced workers		369,535		391,707		415,210		440,122		466,529	
Wage savings tax loss—		−177,377		−188,019		−199,301		−211,259		−233,934	
net wage savings			192,158		203,688		215,909		228,863		242,595
Maintenance expense		−3,000		−8,000		−8,480		−8,989		−9,528	
Maintenance expense tax savings—		1,440		3,840		4,070		4,315		4,574	
net maintenance cost			−1,560		−4,160		−4,410		−4,674		−4,955
Operating/programming expense		−10,000		−10,600		−11,236		−11,910		−12,625	
O/P expense tax savings—		4,800		5,088		5,393		5,717		6,060	
net operating/programming cost			−5,200		−5,512		−5,843		−6,193		−6,565
Subtotals	−400,000		241,398		240,096		233,305		234,585		255,959

[a]Rate of return = 52.8%.

Note: Refer to Table 3 for calculation of wage savings. The ROR analysis shown is based only on the savings generated each period by the robot welding system as compared to the conventional welding system, i.e., savings in labor. All the assumptions and figures used in this analysis are the same as those used in preparing Table 2. The input parameters are: Number of replaced workers = 2.9/shift; and labor savings = \$369,535/year.

the number of workers, the number of accident claims were reduced. Unfortunately, they were unable to quantify this effect. In one economic analysis (Hanright 1988), a 15% saving on welding consumables cost was considered based on the fact that robotic welding systems ultilize the consumable materials more efficiently. The writers were not able to find further published data on this issue. Another important robot characteristic is its flexibility to perform various tasks. For example, the IRB-G6 Robot is capable of assembly, inspection, and polishing. By a tool-changing device, different end effectors can be mounted on the robot. Torch for cutting is one example. This versatility will reduce the initial equipment investment risk. These issues, although not considered in this economic analysis, all tend to make the robot application more attractive. Investigating and quantifying the effect of these issues can be an independent research endeavor.

Sensitivity Analysis

The base input values used in Table 2, represent a hypothetical case for an average fabricator in the industry. The base value will vary for a particular fabricator depending upon company specifics such as size, location, overhead, profitability, technical proficiency, and robot acceptance. Therefore a detailed sensitivity analysis was performed.

In this analysis (Fig. 3), the four base parameters used in Table 2 were varied. These parameters were interest rate, wage rate, robot utilization rate and crew size. Each of the curves in Fig. 3 represents the effect of variation of only one of the parameters on the percent reduction in fabrication cost. For example, if the labor rate happens to be 10% higher than the base value of $31.84/hour used (1.1 times the base value), the percent reduction in fabrication cost would be about 6.1%. This value can be found by drawing a horizontal line from the 1.1 point on the vertical axis. The intersection of this horizontal line and the wage rate curve gives the desired percent reduction in fabrication costs. As can be seen from the graphs in Fig. 3, cost was most sensitive to variations in wage rate followed closely by crew size. The robot utilization rate presents a marketing and inventory concern. Robot utilization rate is the percent of time the robot is not idle excluding robot downtime (repairs, maintenance, programming). The base value used was

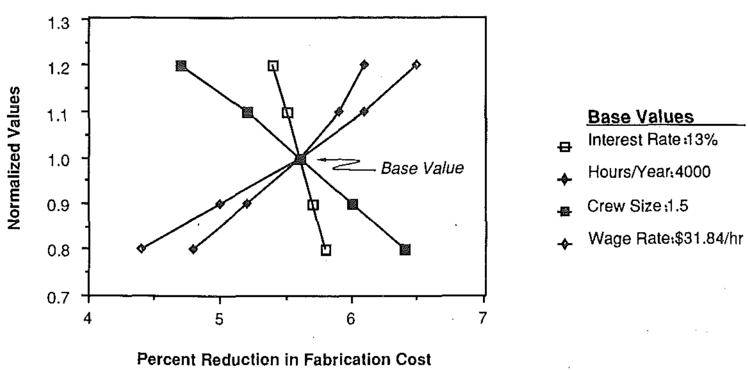

FIG. 3. Sensitivity Analysis: Cash Flow for Robot Investment

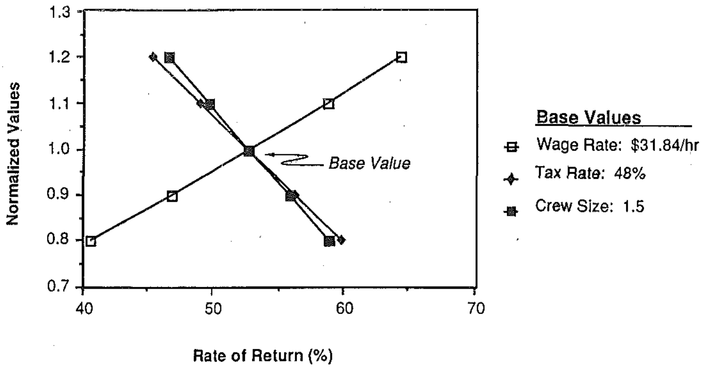

FIG. 4. Rate of Return Analysis

100%. This represents a work load of 667 modules per year assuming 4,000 working hours per year (two shifts). Since most long span bridge redecking projects require between 1,000 to 2,000 modules, to maintain a 100% utilization rate over the five-year life of the robot would require approximately two large projects. Given the increasing number of bridges in need of deck replacement, this assumption is not overly optimistic. As mentioned earlier, bridge deck replacement is a $1–2 billion per year market in the United States (Maser 1987). Based on an interview with a major steel fabricator, in the state of New York alone, the New York State Highway Department, and Throughway Authority are redecking bridges at the rate of more than one bridge per week with over 400 bridges in need of immediate redecking. At this date Baltimore is rebuilding more than 40 bridges in the Jones Falls Expressway alone. Most of these bridges require complete deck replacements (Carr and May 1988).

A sensitivity analysis was also performed on the rate of return table. The effect of variation of tax rate, wage rate and crew size on the rate of return was quantified (Fig. 4). This was done by varying the base values for this variables by ±20%. This analysis shows that even with unfavorable changes in the base values, robot investment remains attractive.

Summary

This study concentrated on determining the percent cost saving that could be realized by automating the steel deck welding operation in a typical fabrication shop. As shown in Fig. 1, the welding operation, including consumables, makes up on average 14% of the total module fabrication cost. Of the remaining 86%, 38% represents material cost, and 48% additional labor cost items such as handling, preparation of material, preheating and postheating if necessary, stress relieving, grinding, rework, coating, administrative and equipment costs. Several of the additional labor items already mentioned have the potential for automation by robotic application or fixed equipment and therefore could provide substantial reductions in the fabrication costs.

Through the use of a robot-welder the fabrication costs of a typical module

was reduced by 5.6%. Since the fabrication cost, on average, makes up 55% of the in-place cost of the module, the total reduction in the cost of the erected module is approximately 3.1%. As mentioned earlier, the initial cost of a steel deck varies anywhere from 5 to 20% higher than its concrete counterpart. If initial costs are the sole criterion used for selecting among alternative systems, then the concrete system still maintains an edge as the least expensive system. However, there are several additional areas in the fabrication process that hold potential for automation and thus could result in additional savings. Also, the use of first time costs as the sole criterion in the selection of a replacement deck system is without adequate justification. Some of the attributes that are not considered by this criterion are: deck's life-span; annual maintenance; benefits in dead load reduction and increased carrying capacity; deck surface performance (skid resistance, smoothness of ride, temperature affects); and inconvenience to the traveling public during construction and project duration.

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