Adaptive Control for Safe and Quality Rebar Fabrication

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Abstract: Rebar fabrication is a labor intensive operation that uses scrap or ''trash'' steel for raw materials and therefore can benefit greatly from improvements in safety, productivity, and quality. Shared control through a human-machine interface may be the best alternative for achieving highest quality standards and improving worker performance in safety and productivity. This paper develops a control scheme for automated rebar bending within the framework of computer integrated construction and presents research focused on the task level control to compensate for springback in the bent rebar. Three major problems are addressed: (1) Conception of a hierarchical computer integrated construction control structure that links rebar fabrication to the other construction project functions: (2) comparative evaluation of alternative algorithms for prediction of springback; and (3) portability of a springback control model that uses real-time electronic sensing. Bending tests were conducted with both a laboratory prototype and an actual shop table bender to experiment with alternative models for in-process springback prediction including a neural network model. Limitations in control system portability were realized in the transfer from the laboratory prototype bender to the shop bender. Springback model evaluations revealed that empirical statistical models, neural networks, and in-process relaxation performed equally well.

INTRODUCTION

With the turn of a new century, the climate of the worldwide construction industry is demanding bold and innovative responses from both today's and tomorrow's civil engineers. Computer integrated construction (CIC) still remains an area with unrealized potential for impacting construction, specifically as it is extended to support automated and robotized processes. It has been possible for some time now for 3D CAD modeling or walk-through data to be shared and submitted electronically for client approval. The latest opportunity and challenge is the effective use of Web-based systems for information sharing among project partners (Rojas and Songer 1999). The benefits of electronic data communication are accessible to any organization with the initiative and resources to invest in developing an integrated system. The potential for using information through this medium, however, has only been partially realized.

Full implementation of CIC requires extending the utilization of the computer's capabilities to the fabrication facility and to the construction site where various types of computer-controlled equipment are poised to receive information from data generated in the design phase (Miyatake and Kangari 1993). The flow of information through the offices of designers and constructors should continue through the field down to the basic task level where it can be utilized to enhance all measures of performance. Briefly stated, computer technology must not only be employed in the creation, communication, and modification of construction plans but also in off-site fabrication and on-site operations through the real-time automated control of construction processes. One candidate of off-site environment for integration is the rebar fabrication facility.

The conception of a CIC environment necessitates an appropriately tailored control structure that affords the ability to convey needed information to the proper entity in a timely manner for decision making and to respond accurately and speedily to changes in the dynamic environment. Hierarchical control, because of its flexibility and its similarity to traditional construction project organization, has been recommended for this purpose (Albus et al. 1981; Bernold et al. 1989; Abraham 1990). This control framework enables the monitoring and control of functions at the local as well as the global level, and it allows the incorporation of ''intelligence'' for automated decision making.

The intelligent computer-controlled execution of construction operations depends on complex models for autonomous and intelligent control of basic tasks. The design, fabrication, delivery, and placement of steel reinforcement bars (rebar) presents ample opportunities for computer integration. Previous work in this area has provided conceptual schemes for integration of the stages of design, delivery, and placement of reinforcing steel, and has shown proofs of some benefits of computer integration and automation (Miltenberger and Bernold 1991; Bernold and Salim 1993; Miyatake and Kangari 1993; Salim and Bernold 1994). Navon et al. (1995, 1996) demonstrated the efficacy of a CAD/CAM data linkage to computer numerically controlled (CNC) rebar fabrication machines. The two problems of a comprehensive (top-to-bottom) control structure for rebar fabrication and of incorporating intelligent control for automated tasks, however, have not been addressed in the literature and remain open to investigation. This paper discusses research directed at these two objectives. A comprehensive control structure based upon computer integrated manufacturing (CIM) concepts is recommended, and results from an experimental program to develop intelligent control models for the critical task of accurate bending are described.

REBAR BENDING IN THE UNITED STATES

Rebar is produced in the United States from scrap or revert material. Inherent limitations in process capability, which is the ability of a machine or process to make a consistent product as defined by specification limits (Wieser 1980; Pond 1994), result in variability in the mechanical properties of the steel product. ASTM A 615 (''Standard'' 1994), which covers the manufacture of plain and deformed rebar produced from steel billets, defines Grade 400 (60) steel only by its minimum yield strength in megapascals (thousands of pounds per square inch). Actual yield strengths can be up to 45% higher than the minimum for this grade of steel. These three factors combine to produce a material with a variable elastic response, known as springback, that requires an adaptive bending apparatus if bending quality (accuracy) is to be maintained.

Although some of the smaller sizes of the approximate annual 2,000,000 t of bent rebar are bent using automatic stirrup

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bending machines, the majority of reinforcing steel is bent using manually operated table benders. The basic technology for these table benders has remained the same for more than five decades with a few innovations in electronic controls and in safety features such as limit switches (*DMI* 1993). Another innovation seen abroad is the double-bend machine that may be found in European fabrication shops and precast facilities (Loders 1992). This latter innovation is not used by U.S. fabricators due to the investment cost. Therefore, the rebar bending operation remains labor intensive and hazardous for the operator. Such injuries as pinched fingers, back injuries from lifting heavy bars, and injuries resulting from the breaking of brittle rebar, the breaking of bending pins, or rebar bending into the operator who may have incorrectly selected or forgotten the bending direction are common in the industry.

In addition to the safety hazard is the issue of waste material that is produced during fabrication. Rebar that is incorrectly bent through test bends or operator error must often be discarded because rebending is not possible. An automated system linked with an integrated database would have the potential to drastically reduce the amount of steel wasted due to bending errors.

Automation of the bending and handling of rebar can provide the answer to the safety hazards of rebar bending while meeting the productivity standards of fabricators and the quality standards of their customers. The handling and positioning of rebar is a relatively straightforward task that may be accomplished through the innovative use of established hardware and software technologies. The actual bending operation, however, is essentially a cold forming process that requires sophisticated controls based upon the ability to respond to variable springback.

Many reinforcing steel and precast reinforced concrete plants around the world employ automated machines for cutting straight and coil rebar, and for straightening and bending coil rebar (Klein 1990; Deichmann 1991; ''Electronically'' 1993). However, coil rebar makes up no more than about 5% of the rebar shipped from U.S. rebar fabrication shops (CRSI 1992). Furthermore, neither these automatic stirrup benders nor the automated double-bending machines for straight rebar intelligently adapt to compensate for springback.

Computer hardware and software and automated control technology may readily be applied to integrate all facets of the process of rebar design, fabrication, and placement. The basic task level performance of producing accurately bent rebars is one of the most critical components in an integrated rebar fabrication system. In order to automate the bending task and meet the quality standards of customers as well as the industry, an intelligent control system that is able to compensate for springback must be established. The failure of U.S. fabricators to embrace the more state-of-the-art benders indicates that new control technology needs to be portable (i.e., transferable from machine to machine). Then existing table benders could simply be retrofitted with the new controller. An adaptive control algorithm that automatically adjusts to the properties of any specific bar could significantly reduce setup time, thus increasing productivity without sacrificing quality.

FUNDAMENTAL ISSUES OF INTEGRATION

Rebar fabrication in the United States, particularly in the eastern region, is primarily driven by internal fabrication schedules. In the current manufacturing paradigm, full integration that incorporates customer requirements is the standard. An organization should move away from having ''stand-alone functions, stand-alone buildings, stand-alone automation, and computers that do not talk to the computers of its partners, customers and suppliers'' (Rucker and Piciacchia 1993). Because fabrication plant operations lend themselves to being analyzed in the manufacturing context, technology developments in CIM may be applied to automated control of operations within a rebar fabrication facility.

CIM may be defined as ''a system which accomplishes optimum production activity through an information network linked to all sections related to production'' (Fukuhara 1991). As such, it consists of ''a number of manufacturing functions combined by computer hardware and software, control systems, and machine tools to produce the highest quality product at the lowest cost'' (Olling 1991). Another manufacturing concept, the flexible manufacturing system (FMS), has been defined as ''a complex production system requiring the efficient allocation of many resources: CNC machines, fixtures, tool magazines, tools, transportation devices and buffers'' (Basnet and Mize 1994). The goal of an FMS is to enable small-batch manufacturing operations to achieve high productivity despite the frequent demand changes. The FMS does not require computer control or automation. It is underneath the umbrella of CIM when computer control of an FMS becomes an objective, and real-time control represents one of the most promising areas of research where control theory can be used (Gershwin et al. 1986). A summary of review by Basnet and Mize (1994) revealed that heuristics and hierarchical approaches tended to offer more practical flexibility and good results for FMS scheduling and control when tested in simulations.

The characteristics of rebar fabrication make it an excellent candidate for FMS application and computer integration. Order lots are small and change frequently. Variations among rebar bend shapes is finite and according to standard types, thus limiting the amount of product flexibility to a manageable level. Stationary work stations offer a convenient opportunity for local and global control within the plant. Also significant is the rebar fabrication facility, which is driven by its link to the dynamic construction environment. If control of the fabrication shop could be integrated into the overall control of the construction project, all parties stand to benefit from the dividends of timely communication and performance of operations.

MODELING FOR CONTROL OF SPRINGBACK COMPENSATION

To achieve automated control for the bending of steel reinforcing bars, the rebar, rebar bender, and the machine-object interaction must be understood and monitored through the application of representative models. The variable characteristic of the material that must be understood by the controller is springback. The peculiarities that make the problem of springback prediction and control significant for research are presented here in a discussion of the unique characteristic of rebar bending.

Moment-Curvature Relationship

The moment-curvature relationship has been the basis for several springback models for rectangular bars that relate the curvature (radius) at the end of bending before release to the curvature after elastic recovery (Lardner 1972; Hosford and Caddell 1983; Pearce 1991). Similar models have been used to either design tool parts to compensate for springback, or to compute, in real time, the necessary overbend to compensate for springback in sheet metals (Sturm and Fletcher 1941; Gardiner 1957).

The most suitable moment-curvature-type model that can be readily obtained for rebar bending is represented by the bending load (force or moment) versus the deformation (bending angle). Although it is certain that the moment-curvature relationship has merit for analyzing the bending of rebar, various parameters of the rebar bending tool setup as well as the rebar

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surface deformations and cross section introduce great complexity into the springback prediction problem. The validity of an empirical approach to predicting springback in sheet metals that takes into account the variation in tool parameters has been supported by other researchers and appears to be a reasonable alternative if the moment-curvature relation alone proves to be inadequate (Strasser 1962; Levy 1984). Success in adaptive control for the bending of sheet metal and extensive use of numerical control for accurate tube bending results in the confidence that some reliable model or strategy may be developed for springback control in rebar bending (''Precision'' 1963; NC tube bending'' 1965; Nicholson 1965; Hardt et al. 1982; Stelson and Gossard 1982).

Rationale for Force/Displacement Control

Force/torque sensors are often used for control of articulated robots through measurement of joint, wrist, and pedestal forces (Rosen and Nitzan 1977). Wrist sensors are often preferred because of their proximity to the object that is being handled. The minimized mass between the sensor and the force source simplifies control as fewer corrections for dynamic machine effects are necessary (Raibert and Craig 1981).

This same concept of simplifying control through proximity to the work can be effective for automation of a cold forming operation such as rebar bending. However, cold forming operations are more appropriately monitored using force/displacement control. In this strategy, the position resulting from the force interaction between manipulator and workpiece is monitored simultaneously with the force applied to the workpiece. In this way, applied force can be related to material deformation. This is precisely the type of strategy which can employ a moment-curvature-type model for springback control.

Concept of Impedance Control

An appropriate model of the interaction between the manipulator and its environment is necessary for achieving precision in accurately commanding the manipulator's motions. The concepts for admittance, impedance, and impedance control have been used in applications where a manipulator has mechanical contact with the workpiece (Hogan 1985; Lasky and Hsia 1991; Liu and Goldenberg 1991).

A manipulator, when coupled with the object to be manipulated, assumes the behavior of an impedance, accepting motion inputs and yielding force outputs. The object (or environment) takes on the form of an admittance, accepting force inputs and yielding motion outputs. In this concept, the controller uses relative sensory measures to constantly readjust the control parameters of the manipulator (the impedance). The approach of controlling a manipulator by providing it with not only a motion command but also with a response to any disturbances that cause deviations in the execution of that command is termed impedance control (Hogan 1985). Based on these definitions, a rebar bender acts as an impedance whereas the rebar itself can be modeled as an admittance.

The rebar bending task requires physical contact in which the bender and the rebar exhibit a measure of compliance (yielding). The interaction of a compliant manipulator and a compliant object involves dynamic parameters and contact conditions that complicate the task of control (Annaswamy and Seto 1991). The rebar bender compliance may be viewed as a mass-spring-dashpot system (i.e., having inertia, damping, and stiffness parameters) (Liu and Goldenberg 1991). To develop the necessary control laws, the relationships between motion and deviations in observable measure must be recognized.

PROPOSED COMPUTER INTEGRATION FOR REBAR FABRICATION

Previous research in process planning for the design, fabrication, and delivery of rebars served as the foundation from which this research was extended. A CAD-integrated rebar placement planning (CRPP) system was proposed by Salim and Bernold (1992) for increasing the productivity of rebar design, detailing, fabrication, delivery, and placement. The benefits of this system to rebar placement productivity were later proven by the same researchers (Salim and Bernold 1994). Fig. 1 contains a schematic of the CRPP which has been adapted to show the extension to this work.

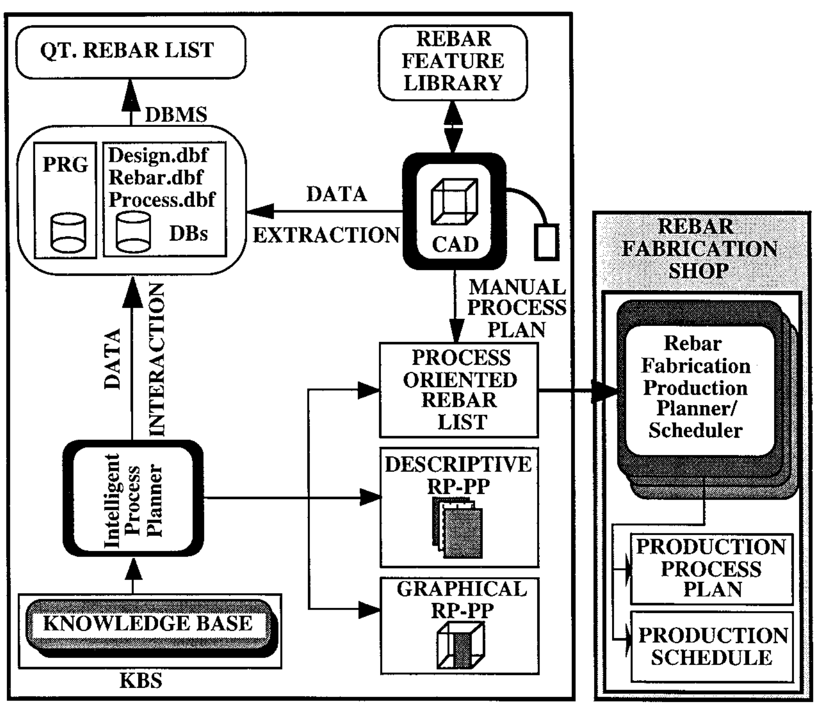

FIG. 1. Information Link between CRPP and Rebar Fabrication Shop

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Because the CRPP was conceived as a tool to be used ideally by the specifier, it is shown to be outside the realm of the rebar fabrication shop. As seen in the larger rectangular box, the CRPP system provides four outputs, one of which is a quantity (QT.) rebar list. This list represents the standard detailing information that fabrication shops use as an input for generating production schedules. The process oriented rebar list (hereafter referred to as the rebar list) differs in the way it groups bars for bundling to facilitate field placement. While either output may be used, the latter has been shown to provide great benefit for field productivity and is therefore shown as the preferred input to the fabrication shop operation. The rebar list may be passed to the rebar fabrication shop where it serves as an input to a planner/scheduler, here referred to as the rebar fabrication production planner/scheduler (RFPPS). A model for combining these functions of production scheduling, process planning, and decision-making modules that make use of the manufacturing resource database was proposed by Zhang and Mallur (1994). The customer's projected schedule would be another input into the RFPPS. As a component of the FMS, the RFPPS outputs a fabrication process plan and a schedule for filling the rebar order. Other functions within the FMS are indicated by the blocks situated in shadow behind the RFPPS in Fig. 1.

Gupta and Buzacott (1989) represent the FMS as a system consisting of three major components: (1) The ''manager''; (2) the controller; and (3) the production unit. It is this system within the rebar fabrication plant which makes use of the rebar list that is generated by the CRPP. The manager maintains the RFPPS. The schematic of this FMS has been adapted here to demonstrate integration and is shown in Fig. 2.

After being received by the collective entity known as the manager, the rebar list and the production schedule are submitted to the FMS controller. The FMS controller is normally a central computer which performs the supervisory tasks of communicating with the dedicated controllers of the various machines in the production unit. The production unit, consisting of all production machines, material handling units (transport), and data gathering equipment, receives the allocation of resources from the FMS controller. It is at this level that the rebar fabrication tasks are performed. From each of these stations, status information is returned to the FMS controller so that it may efficiently coordinate the production operations and update instructions according to any changes that may occur in production unit capacity or production objectives.

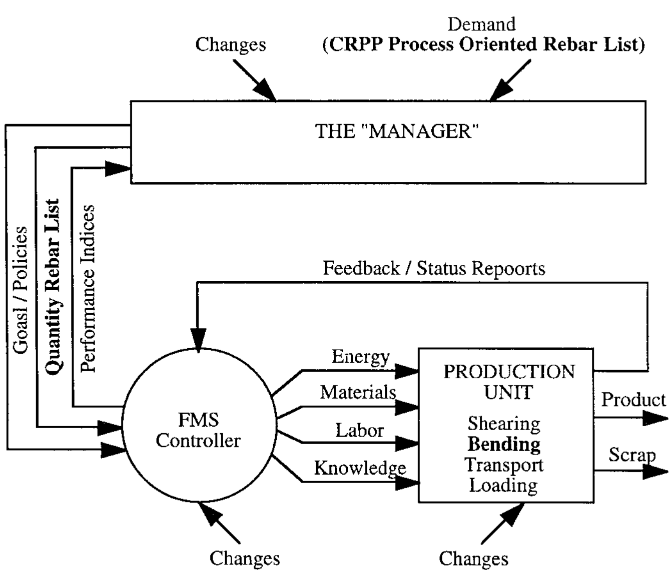

FIG. 2. Adaptation of FMS Framework to Rebar Fabrication [Adapted from Gupta and Buzacott (1989)]

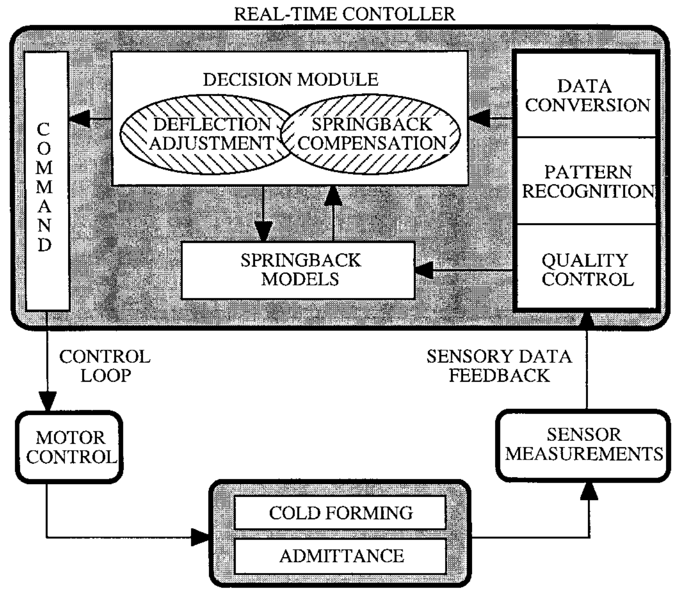

FIG. 3. Schematic of Adaptive Control Structure for Automated Rebar Bending

This type of control structure, where the FMS controller acts as supervisor and coordinator without performing direct control tasks, is quite appropriate for an operation such as rebar fabrication. When close, continuous synchronization is not critical, decentralized control of specific tasks is more feasible, and more of the centralized control can be devoted to status monitoring functions and overall system updates (Shimano et al. 1984).

A schematic of the local (basic task) real-time control system proposed for the automated bending of rebar is shown in Fig. 3. This model has been updated from earlier versions that have been presented (Dunston and Bernold 1994a,b). The control loop begins with the desired bend angle as the initially commanded angle. This command is executed in the activation of the bender motor and results in the bending of the rebar. The rebar responds as an admittance, providing information on its specific plastic behavior to sensors on the automated bender. The sensory data is returned to the controller for conversion, pattern recognition, and quality control (springback model performance evaluation). The decision module calculates the predicted springback and the necessary adjustment to overcome deflection in the mechanical system (impedance adjustment). The sum of this compensation is then sent as a subsequent bending command thus completing the control loop.

As pointed out by Gupta and Buzacott (1989), the illustration of the FMS in Fig. 2 suggests the existence of a hierarchical control mechanism. Indeed, this entire system of controller and planners as outlined may be integrated within the state-based framework for hierarchical control developed by Abraham (1990). Status information can flow up the hierarchy from the rebar bender controller to the FMS controller, from the FMS controller to the construction site, and from there to the management office computer to contribute to an up-to-date assessment of the construction project status.

MACHINE LEARNING ALTERNATIVE

The classical approach to control relies upon extensive knowledge of the problem domain (Luger and Stubblefield 1989). This type of control is adequate as long as all of the significant parameters are known, measurable, and accounted for in the control laws. A problem occurs, however, when a new condition or situation arises and the control program has

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no way of responding or even recognizing the inadequacy of its solution. A truly adaptive controller that possesses a capacity for adjusting its prediction through some machine learning technique might be necessary for meeting the challenge of rebar bending. Also referred to as autonomous knowledge acquisition, early research in machine learning was involved closely with pattern recognition (Kusiak 1990). Neural networks make up one of the more active areas of research in machine learning (Weiss and Kulikowksi 1991).

The design of neural networks is loosely based upon the idealized representation of biological neural connections (Taylor 1993). There are four characteristics of neural networks that make them suitable for springback prediction: (1) Capacity for continued learning when in operation; (2) insensitivity to noise; (3) real-time capability; and (4) capacity for generalization. These particular strengths should enable a well-designed neural network to efficiently handle the numerous variables that are present in the cold bending of rebar.

TABLE BENDER CONTROL SETUP

A schematic of an adaptive local control structure was shown in Fig. 3, and that control structure models the physical controller-machine setup that was devised for this research. Fig. 4 is an illustration of the proposed hardware setup for local control of the bending task. Consistent with Fig. 3, the control computer commands the turntable motion and receives sensory feedback for analysis and springback prediction. One feature that is not as evident in Fig. 3 is the transmission of position feedback. This is necessary for measurement and correction of the deviation from the commanded position (impedance control).

In addition to control, position measurements are used along with bending load measurements (admittance) to create the bending curve that may be used for analysis of the rebar to predict springback. Note that the position of the load sensor is collinear with the backstop ram in order to minimize the dynamic machine effects between the sensor and the machine-object interaction. The next sections briefly describe how tests were conducted using this model concept to obtain data that could be used to develop a model for the real-time prediction of springback.

EXPERIMENTAL INVESTIGATION

The foregoing discussion lays out a control structure that is rich in opportunities for experimental investigation and system development. Experiments to be discussed here were aimed at investigating the problem of springback prediction in the bending of rebar. A sensor-equipped shop table bender was made available for the experiments by a leading U.S. rebar bender manufacturer. An earlier laboratory prototype table bender afforded the opportunity for a focused preliminary analysis of the cold bending operation (Dunston and Bernold 1993, 1994a). Critical lessons learned from the laboratory prototype tests guided the performance of tests conducted using the shop bender. An illustration of the laboratory prototype is shown in Fig. 5. Bending load was monitored via strain gauges mounted on the center axle of the rotating table, and rotational position was controlled directly via a stepper motor driven by a CNC controller. Portability was assessed by the attempt to transfer the laboratory prototype benders control algorithm to the shop bender.

The shop table bender model was designed to bend rebar as large as size #14 which has a nominal diameter of 43.00 mm (1.693 in.). A bender controller ''head,'' with a microprocessor designed and manufactured by another division of the same manufacturing company, was used for the direct control of bending. Proprietary concerns over revealing the control code prohibited a computer interface with this controller that would allow for closed loop control from a separate computer as depicted in Fig. 4.

Differences in design features between the laboratory bender and the shop bender resulted in dissimilar sensor retrofits. One of the backstop rams of the shop bender was retrofitted with an adjustable extension that included a load cell for measuring the axial load experienced by the backstop ram during bending. Fig. 6 shows this load cell as it was installed on the shop bender. Using a specially designed bracket, an optical encoder was situated atop the center pin for measuring the table bender's rotation. Together these sensors provided the critical sensory information for investigation of the springback prediction problem.

Grade 400 (60) rebars of sizes #4, #6, and #8, supplied by a local steel fabricator, were selected for the bending tests because they covered the range of the greatest percentage of

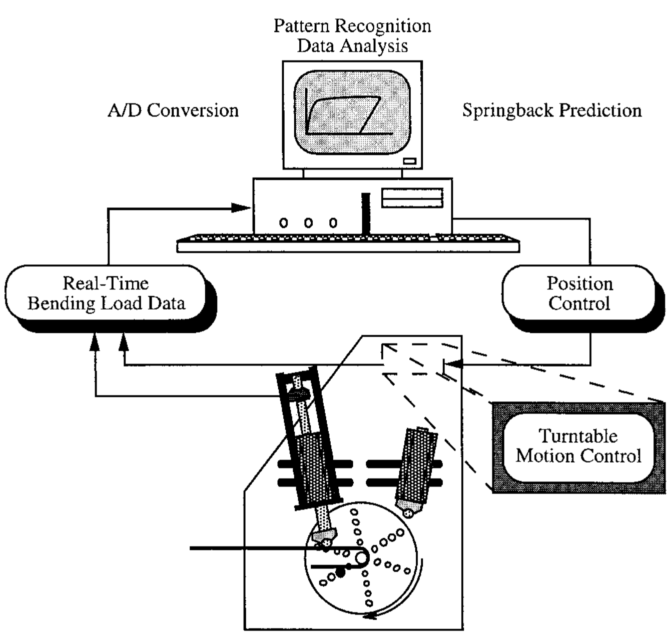

FIG. 4. Schematic of Integrated Adaptive Control System Setup

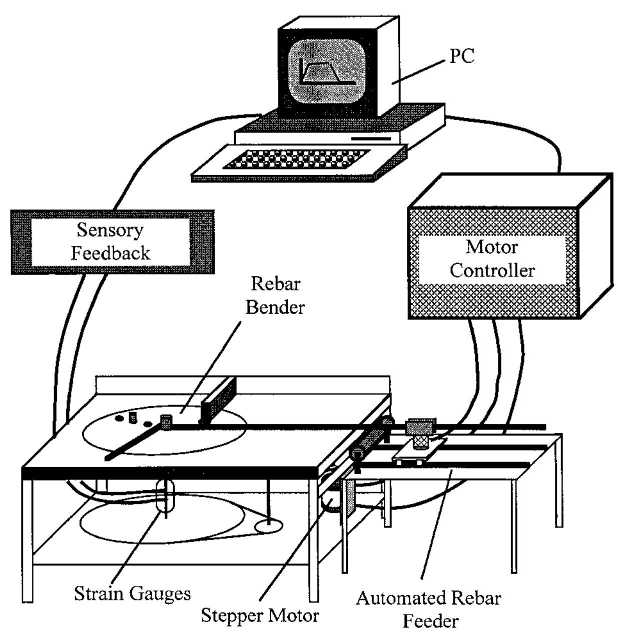

FIG. 5. Experimental Laboratory Prototype Table Bender with Automated Feed

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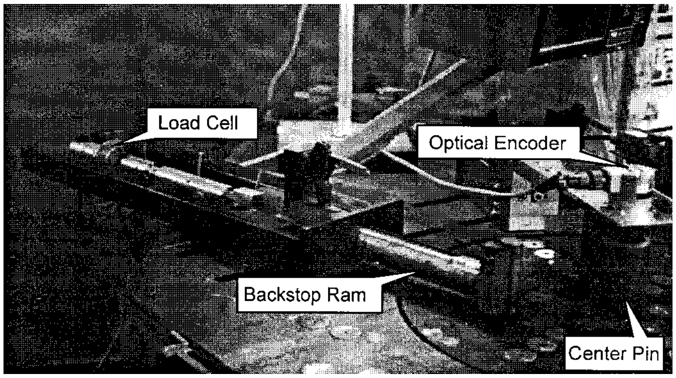

FIG. 6. Sensor Retrofit of Shop Bender for Experimentation

bars that are bent, and because the required bending loads fell within the operating range of the load cell. The laboratory prototype bender only had the capacity to bend up to size #4 rebar.

For each size of rebar, batches were selected so that reported yield strengths were equally balanced between the normal lower and upper ranges for Grade 400 (60) rebars. The lowest documented representative yield strength was 438.5 MPa (63.6 ksi) and the highest was 599.9 MPa (87 ksi). There was a gap between the upper and lower values from about 497.8 MPa (72.2 ksi) to 545.4 MPa (79.1 ksi).

Test bends were performed using a scheme that varied the parameters of orientation of the longitudinal surface deformations (ribs), bending angle, and rebar size. The significance of rebar orientation in bending was described in previous articles (Dunston and Bernold 1993, 1994a). Individual bars were bent in different locations to 45°, 90°, 135°, and 180°, increments consistent with standard bend angles.

The statistically based testing scheme, best described as an unbalanced block design, was organized to test two batches for each rebar size. The test design was performed once for each bar size and then repeated with new batches of steel to increase the overall size of the data set. A summary of the experimental results follows.

EVALUATION OF CONTROL MODELS

Two experimental objectives are presented here. The first was whether the laboratory prototype bender control model was portable (i.e., the degree to which it could be simply transferred to the shop bender). Because sensor options were not the same, the form of the most effective regression models for springback prediction was the major criteria for answering this question. The second objective was to compare the accuracy of various springback prediction models using the shop bender. Because the number of uncontrollable machine variables discouraged use of the moment-curvature relationship, comparative tests focused on evaluating three empirical prediction models based upon the following techniques: (1) Multiple linear regression; (2) in-process relaxation; and (3) neural networks. The quality parameter used for comparison was the difference between the predicted springback and the measured springback angle.

Laboratory Prototype Bender Regression Model

The springback prediction model that was found to be the most accurate for the laboratory bender was only developed for size #4 rebar due to the capacity of the machine. The prediction model, a first-order polynomial equation, included terms that were based upon three factors: (1) The bend angle; (2) an estimate of the torque (bending load) at yielding; and (3) the orientation of the rebar. An interesting feature of the empirical equation was an interaction between the bend (target) angle and the estimated yield torque. A complete description was reported by Dunston (1994).

Shop Bender Regression Models

Based on the specific shop bender machine setup and the data that was obtained, two regression models were developed for rebar sizes #4, #6, and #8. The first model, a second-order polynomial, was a general equation that covered the all three rebar sizes and was based upon the independent variables of bend angle and rebar size. The second, a first-order polynomial, was a size specific model that was based solely upon the bend angle as the independent variable. Both equations were described by Dunston et al. (1996).

In-Process Relaxation Control Model

The second method called for relaxing the bending load at a rotational position that was about 10° short of the bend angle. This approach is akin to the bender operator's standard practice of applying a second turn of the table after inspecting a bend that is short of the target. Previous testing indicated that very little change in springback should occur over the range of these last few degrees of bending (Dunston 1994). This method would be more time consuming in practice, but was deemed a good alternative in the event that other methods were not accurate enough. Efforts to enhance the performance of the statistical models by the addition of the slope of an 80% in-process unloading curve or a complete springback measurement did not increase the accuracy of those models. This result prompted the decision to use this information as a sole predictor of springback as it was rationalized to be a redundant estimator when combined with the other regression factors. An alternative of 80% relaxation (with respect to bending load) served to reduce error by using data acquired before points of contact between the machine and the rebar are lost (as in a complete release of the rebar).

Neural Network Control Model

Consistent with the statistical approach, neural networks were configured and trained for single rebar sizes as well as for combined sizes. Because of the larger training set, the best performance was achieved with the combination of different sizes. Training was performed using two-thirds of the total 144 data sets, and the network performance was tested on the remaining sets. Comparisons with the statistical models were based upon the same division of the data for model development and testing. The features of the neural network model were described by Dunston et al. (1996).

Comparative Evaluation of Shop Bender Control Models

Comparisons were made between the regression models and the neural network model and between the regression models and the in-process relaxation models for predicting springback. Although the recommended standard of $\pm 2.5°$ is only applied to 90° bends and hooks (*Manual* 1990; ''Standard'' 1990), performance was consistently evaluated based upon this objective criteria for all degree bends.

The RMS errors (the average error in absolute terms) indicated a similar performance between the regression and neural network models; the range of error being virtually the same in each case. The standard deviations also were good, only slightly exceeding the 2.5° threshold for 95% of the cases. The neural network model demonstrated less of a central tendency in its prediction performance indicating a systematic discrep-

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ancy, the source of which remains unknown as the ''knowledge'' contained in the neural network is not transparent.

New bending tests were conducted to obtain data for the comparison between in-process relaxation control model and the two regression models. The general and size-specific prediction equations were the same ones that were developed for the original data set of 144 bends. RMS error values once again indicated similar average performances by all models. It was surprising that the relaxation strategies did not produce better results as they are characterized by relatively large ranges of error. It is believed that the inability to fully interface with the shop bender controls allowed error to be introduced.

IMPLICATIONS OF TEST RESULTS

Regression models for the laboratory prototype bender and the shop bender did not contain all the same variables, which indicates that the degree of controller portability is limited by the machine design. The different types of sensors—axle-mounted strain gauges versus backstop-mounted load cell—is believed to explain part of the difference. The drive transmission designs and the substantial difference in mass between the two machines were also likely explanations for the lack of agreement in the regression model terms (independent variables). Of the models investigated, only the in-process relaxation models and the neural network models could be expected to function reasonably in a fully portable control system. Their parameters were data-reliant rather than machine-reliant.

Although they performed quite well considering the number of variables and the relatively small units of the quality measure, none of the proposed springback control strategies conclusively (100%) meet the quality criteria of $\pm 2.5°$. An indirect comparison with a human operator's performance reveals that the models also do not exceed the performance of a highly skilled human operator. One day spent randomly sampling the accuracy of bends produced by a skilled ''master bender'' operator revealed that quality tended to fall below the objective criteria only when complex bend patterns were attempted. When specifications called for numerous bends on one rebar, particularly in different planes, quality fell to a level similar to that demonstrated by the prediction models.

These facts imply that the most practical approach to control is a human-machine interface wherein a skilled operator and an automated controller share control responsibilities. An investigation of this option might include field tests that combine a skilled operator with an automated controller. This type of control scenario also raises the question of how the operator's judgment would be impacted by having knowledge of real-time sensor measurements. Such a control strategy would offer the opportunity to explore the impact of automated and/or semiautomated control upon safety and productivity, two important performance measures that were not addressed within the scope of this research.

Because the bending accuracy appears to depend upon some factors that are either unknown or hidden from the user, the capacity for learning is an attractive feature for a rebar bending controller. Variables such as the wearing of machine parts or changes in the production source of stock material would likely result in a need to periodically ''refit'' any model. Neural networks or regression algorithms could be tested for their long-term performance under these conditions.

CONCLUSIONS

As the experimentation presented by the writers has focused upon the primary objective of automated control to achieve bending accuracy, the results demonstrate the following contributions to be state of the art:

1. A hierarchical framework for linking the automated control of rebar bending to the higher level functions of a construction enterprise has been presented. This framework incorporates the concepts of CIM for the rebar fabrication facility and integrates it with the design and production phases of the construction project.
2. A portable feedforward control model for adaptively bending rebar through the use of automatic force and position measurements may be developed and modified for transfer to different models of table benders. However, the springback prediction algorithms must be selected for reliance upon data rather than upon machine and sensor design.
3. Greater bending accuracies must be achieved before the adaptive control of rebar bending may yield an increase in quality over simple manual bending. The consistency of proposed springback control strategies will offer quality increases if smaller variances in performance are achieved. Machine learning and further studies to quantify process parameters may yield the necessary improvements in accuracy.
4. Results of the comparative springback prediction test indicate that shared control between a human operator and an automated system may be a good strategy for achieving desired bending accuracy. The human-machine interface could include control for additional fabrication tasks (e.g., shearing and positioning) and thus have a positive impact on operator safety and process productivity as well as bending quality.

A necessary step toward implementing automation in the operation of table benders is to develop and test several models of fully automated shop benders with control interfaces that would allow closure of the control loop. Such integrated experimental facilities would be a test bed for further refinement of springback control models, for validating the portability of various control models, and for extending the best springback prediction models to the full range of rebar sizes. The impact of automating control of the entire rebar fabrication operation on safety and productivity should also be investigated. The recommended human-machine control interface should be analyzed for its effect on the fabrication operation as well as the product quality. The model proposed for full integration of adaptive control in the rebar fabrication environment may also be modifiable for application to other construction material fabrication or prefabrication operations.

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