AUTOMATED REBAR BENDING

Computer Integrated Construction (CIC) is an area with unrealized potential for impacting construction, specifically as it is extended to support automated and robotized processes. Full implementation of CIC requires extending the utilization of the computer s capabilities to both 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. 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 off-site environment for integration is the rebar fabrication facility.

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. This research, an extension of other work in intelligent process planning (IPP) at the Construction Automation & Robotics Laboratory, was directed at realizing a comprehensive control structure for rebar fabrication based upon computer integrated manufacturing (CIM) concepts. Results from an experimental program to develop intelligent control models for the critical task of accurate bending are described.

Rebar Bending in the US

Rebar is produced in the US from scrap or revert material. Inherent limitations in *process capability* result in variability in the mechanical properties of the steel product. Standards for the manufacture of rebar produced in the US merely define minimum yield strengths. Actual yield strengths can be up to 45% higher than the defining minimum for Grade 400 (60 ksi) steel. These three factors combine to produce a material with variable elastic response, known as springback, that requires an adaptive bending apparatus if bending quality (accuracy) is to be maintained.

While some of the smaller sizes of the approximate annual 2 million tons of bent rebar are bent using automatic stirrup bending machines, the majority of reinforcing steel is bent using manually operated table benders. More highly automated double-bend machines found in European fabrication shops and precast facilities are 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 due to 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. A final concern is the cost of generating and discarding waste material that may result from human operator error because rebending is not possible. The critical bending operation is essentially a cold forming process that requires sophisticated controls based upon the ability to respond to springback which varies between individual bars, heats (batches), and bend shapes.

The lack of interest from US fabricators to embrace the more state-of-the-art benders indicates that new control technology needs to be portable, that is, 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.

Levels of Control and Experimental Setups

Previous research at CARL in process planning for the design, fabrication, and delivery of rebars served as the foundation from which this research was extended. This work produced a CAD-Integrated Rebar Placement Planning (CRPP) system as 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 demonstrated by the same researchers (Salim and Bernold 1993; Bernold and Salim 1994). Fig. 1 contains a schematic of the CRPP which has been adapted to show the extension to this work.

Since the CRPP was conceived as a tool to be used ideally by the specifier, it is depicted outside the domain of the fabrication shop. As seen in the larger rectangular box, the CRPP system provides four outputs, one of which is a quantity rebar list. This list represents the standard detailing information that fabrication shops use as 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 process oriented 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). 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.

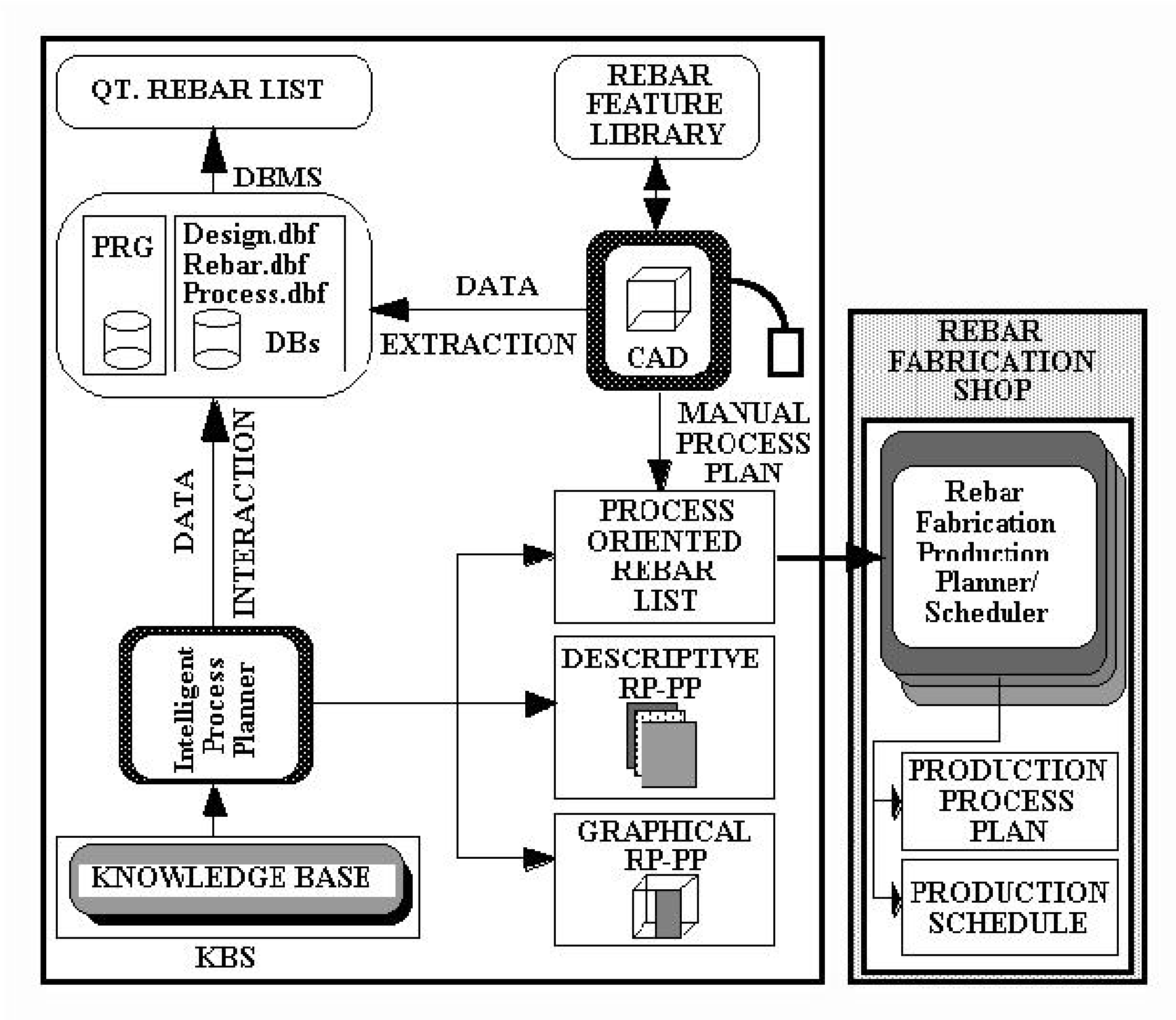

FIG. 1. Information Link between CRPP and a Rebar Fabrication Shop

Gupta and Buzacott (1989) represent the manufacturing FMS as a system consisting of three major components: 1) the "manager," 2) the controller, and 3) the production unit. It is such a 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 system has been adapted demonstrate the proposed integration and is shown in Fig. 2.

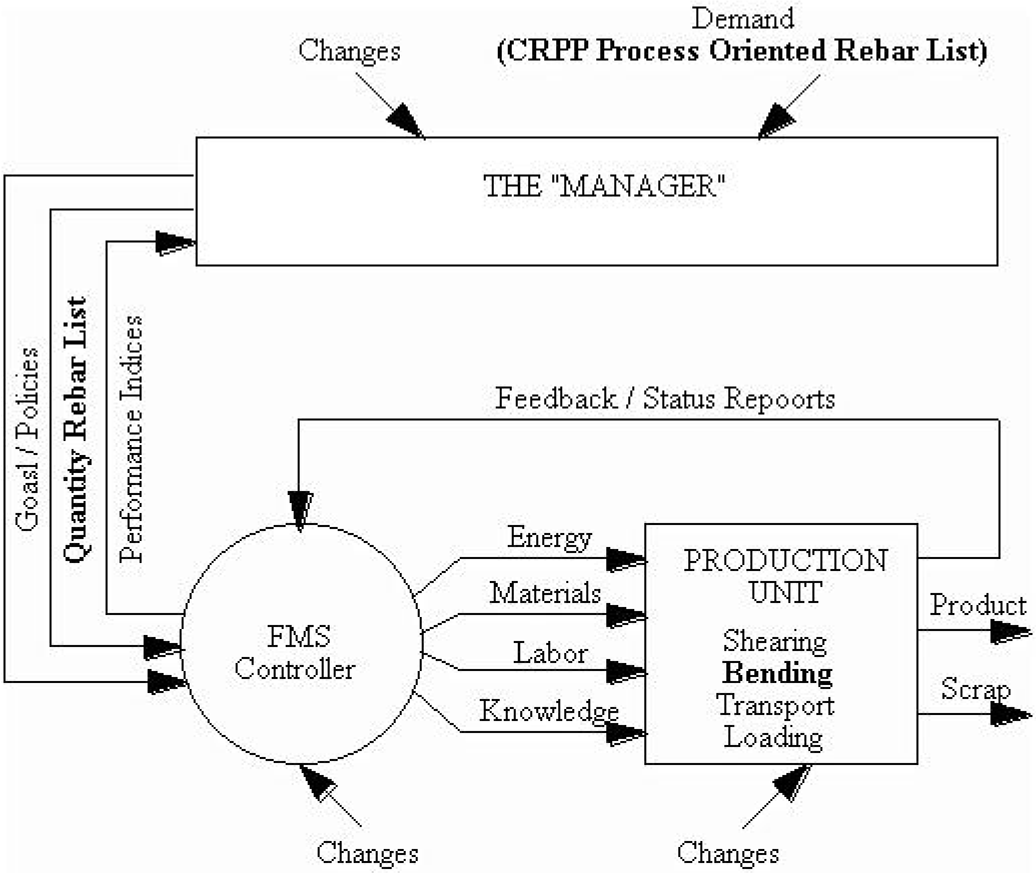

FIG. 2. Adaptation of FMS Framework to Rebar Fabrication (adapted from Gupta and Buzacott 1989)

A schematic of the local (basic task) real-time control system proposed for the automated bending of rebar is shown in Fig. 3. 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 strength characteristics 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.

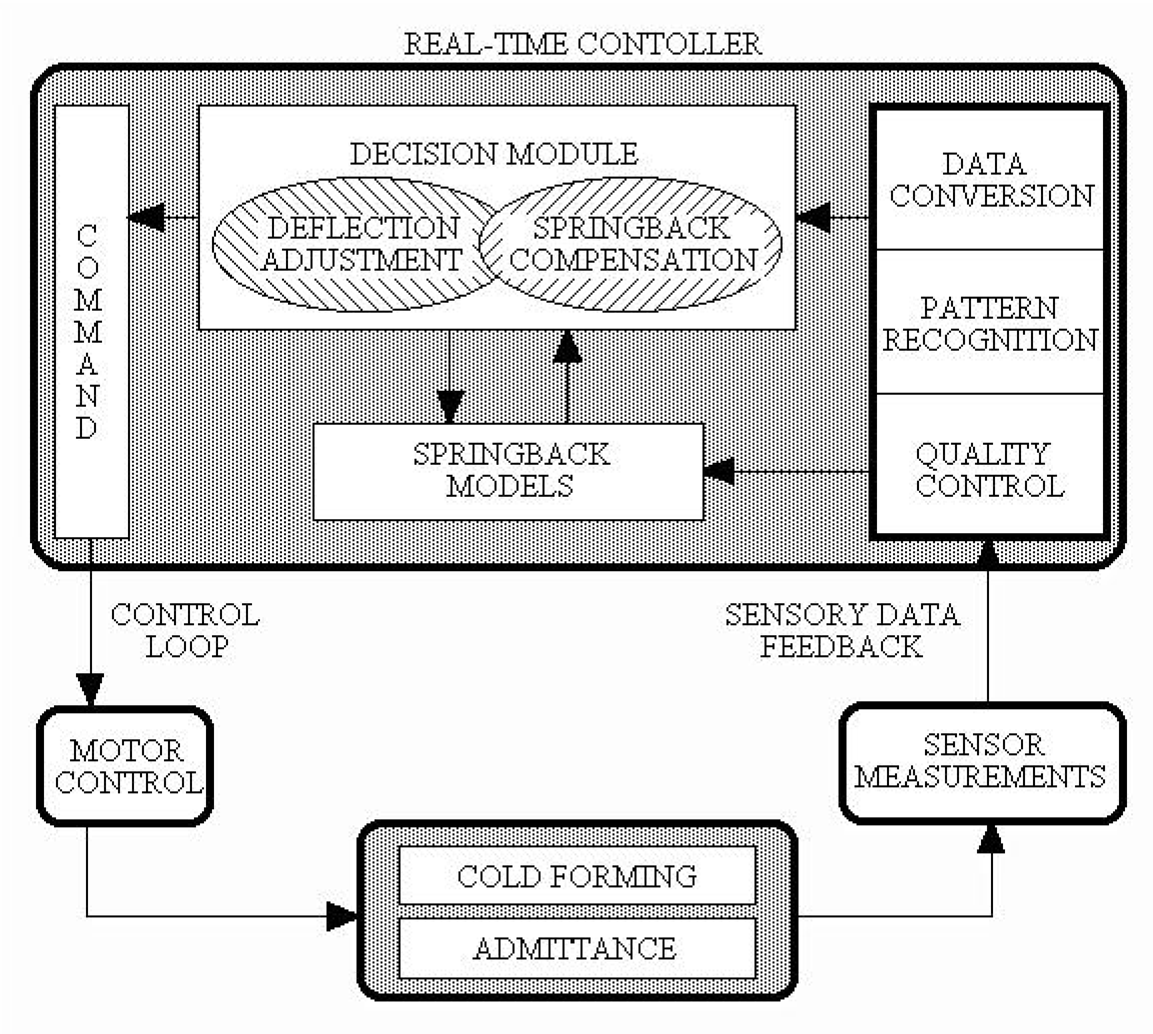

FIG. 3. Schematic of Adaptive Control Structure for Automated Rebar Bending

Fig. 4 illustrates 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).

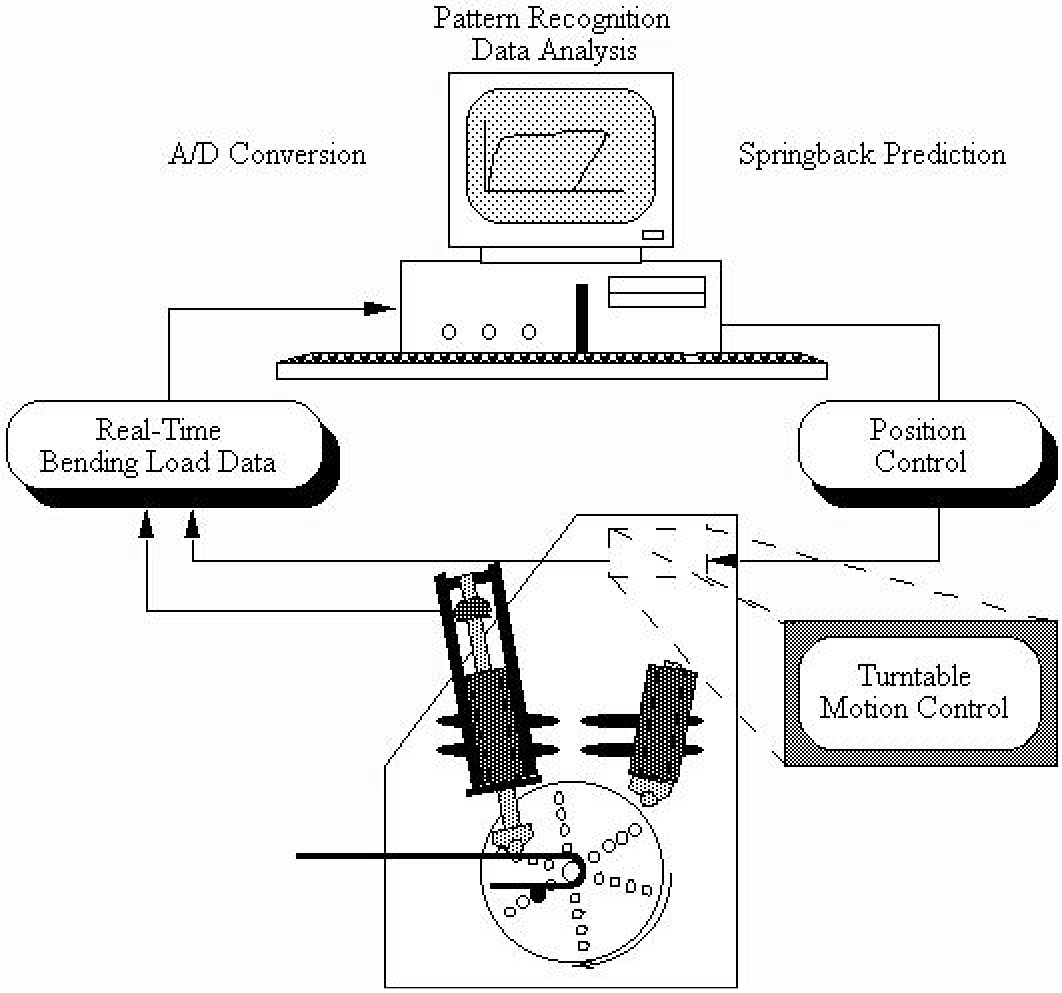

FIG. 4. Schematic of an Integrated Adaptive Control System Setup

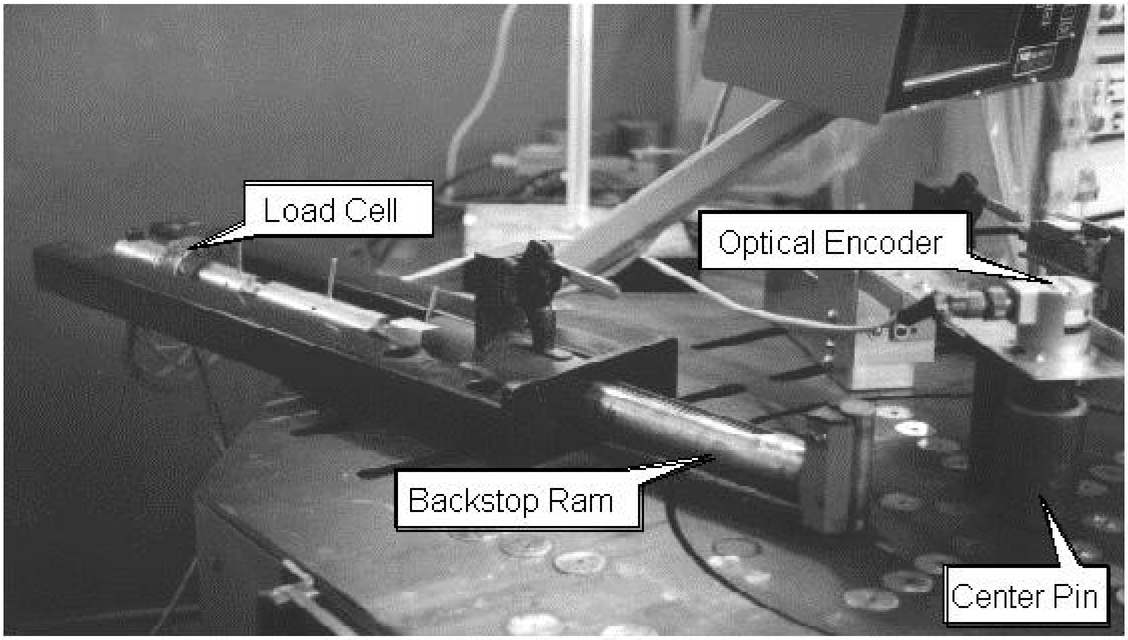

FIG. 5. Sensor Retrofit of Shop Bender for Experimentation

EXPERIMENTAL INVESTIGATION

Experiments were conducted to investigate the problem of springback prediction in the bending of rebar. A shop table bender was equipped with sensors for monitoring bending load and position (angular deformation) as shown in Fig. 5. This data was collected from 144 bends of Grade 400 (60) rebars of sizes #4, #6, and #8. 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.

For each size of rebar, batches were selected so that reported yield strengths were equally balanced between the normal lower and upper ranges. The lowest documented representative yield strength was 438.5 MPa (63.6 ksi) and the highest was 599.9 MPa (87 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 statistically based testing scheme, an unbalanced block design, was organized to test two batches for each rebar size. The test design was performed twice to increase the overall size of the data set to 144. Models were based upon two-thirds of the data and performance comparisons were conducted using the remaining third.

EVALUATION OF CONTROL MODELS

A primary objective was to compare the accuracy of three empirical springback 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.

Two regression models were developed. 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 which was based solely upon the bend angle as the independent variable.

The second method, a more time consuming practice, 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.

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.

The issue of portability of the control algorithm was tested by comparison of the empirical control algorithms to that developed for an earlier laboratory prototype bender.

Comparative Evaluation of Shop Bender Control Models

The RMS errors (the average error in absolute terms) indicated 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 discrepancy, the source of which remains unknown since 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. RMS error values once again indicated similar average performance 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.

CONCLUSIONS

Some of the results of our research demonstrate the following:

1) A hierarchical control for automated rebar fabrication (springback control in particular) has been presented that incorporates the concepts of computer integrated manufacturing for the rebar fabrication facility 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) 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. The impact of automating control of the entire rebar fabrication operation on safety and productivity should also be investigated. A 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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