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Intelligent control for robotic rebar bending

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Abstract

Computers are becoming essential tools for integrating design, planning, fabrication, and construction. Computer-controlled construction equipment are poised to receive information from data generated in the design phase. The robotic execution of construction operations, however, depends on complex models for autonomous and intelligent control. This paper discusses the implementation of a strategy for the robotic bending of straight steel reinforcing bars (rebar) and presents the results of experimental work with an actual testing facility. Cold forming principles and the mechanical behavior of rebar are examined to develop rules for a real-time controller. Focus is placed upon exploring the dynamics between the bender and the rebar. The concepts of impedance, admittance, and compliance of both the machine and the environment are discussed in the context of control strategy development.

1. INTRODUCTION

The ultimate goal of Computer Integrated Construction (CIC) is the full linkage of all phases of a construction project, namely design, planning, fabrication, and construction. The flow of information through the offices of designers, fabricators, and constructors should continue to both the fabrication shop and the field where such information can be utilized to enhance productivity, quality, and safety. This information may then be employed in the real-time automated control of construction processes.

One area of construction that has been targeted for comprehensive research by the Construction Automation & Robotics Laboratory (CARL) at North Carolina State University is that of the design, delivery, and placement of steel reinforcement bars (rebar). A component of this research deals with the development of a computer-controlled bender for straight bars with real-time adaptive control capabilities. The current stage of research deals with understanding the behavior of the rebar and developing a model for controlling the operation in order to achieve consistently accurate bent bars.

Machine manufacturers have already developed automatic rebar benders that bend the small diameter coil rebar, and this technology is currently in use by rebar fabricators worldwide. However, these small size rebar only make up a fraction of the rebar typically used in concrete construction. The technology for automatically bending straight bars can dramatically change the traditional rebar fabrication process by increasing the quality of bending as well as just-in-time production and delivery, thus increasing the efficiency of rebar placement.

2. MECHANICS OF BENDING AND SPRINGBACK

The bending of rebar is a cold forming process that is affected by two physical aspects of the steel bar: (1) the moment of inertia of the rebar cross section and (2) the elastic-plastic properties of the reinforcing bar. The effect of the moment of inertia can be seen in Figure 1 below. Longitudinal ribs, a result of the hot rolling process and common to all rebar deformation patterns, add to the moment of inertia about the axis of bending when these ribs are oriented perpendicular (horizontal) to the bending axis. A collinear (vertical) orientation of the ribs relative to the bending plane results in a smaller moment of inertia and therefore requires less bending effort.

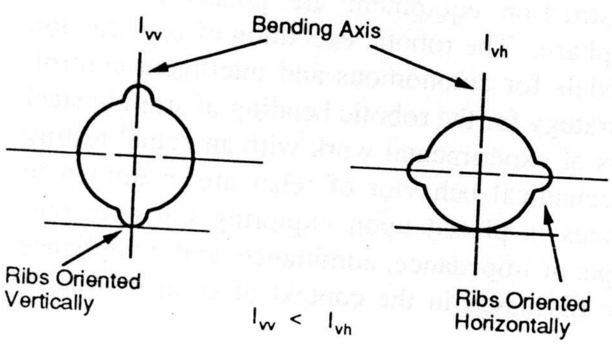

Figure 1. Effect of rebar orientation on moment of inertia.

The elastic-plastic properties of the reinforcing steel manifest themselves in the development of stresses during the bending process. The resolution of these stresses results in what is called springback, the major obstacle to accurate bending of rebar [1]. In the literature on the cold forming of metals, mainly sheet metal, the topic of springback has received the most attention [2, 3]. The analysis of the material behavior is based upon the conventional cantilevered beam theory for bending. The same general principles that apply to bending sheet metal also apply to the bending of bars.

Springback is governed by the variation of stresses that develop during bending. The largest tensile stress develops initially at the outer surface of the rebar and decreases toward the neutral axis. As bending continues, the zone exceeding the yield stress moves inward towards the neutral axis. Thus, the plastic region increases while the elastic region around the neutral axis decreases. When the final bend angle is reached and the bar is released, the elastic band attempts to return to a straight orientation, but the permanently deformed plastic band resists this motion. The resulting stress equilibrium is observed as a springback. The variables known to effect springback are elastic limit (or yield strength), bend radius, bend angle, and thickness (or diameter) of the metal workpiece. The only feasible method for overcoming springback in rebar is overbending, the traditional approach employed by the skilled rebar bender operator who relies upon his judgement to compensate for springback.

3. EXPERIMENTAL FACILITY

A prototype rebar bending system, named ARB (Automated Rebar Bender), for conducting empirical studies and testing of control strategies has been built at CARL. An illustration of the hardware used in the computer integrated system is shown in Figure 2. A 386 PC is used to operate a stepper motor via a Centroid controller (model CNC-3). Commands are sent from the PC to the motor controller through a communications port (COM1). The stepper motor drives the rotating table of the rebar bender through two chain-and-sprocket sets. The bending peg maintains a fixed point of contact as it wraps the bar around the center pin, but a roller bearing on the holdback allows free translation of the bar.

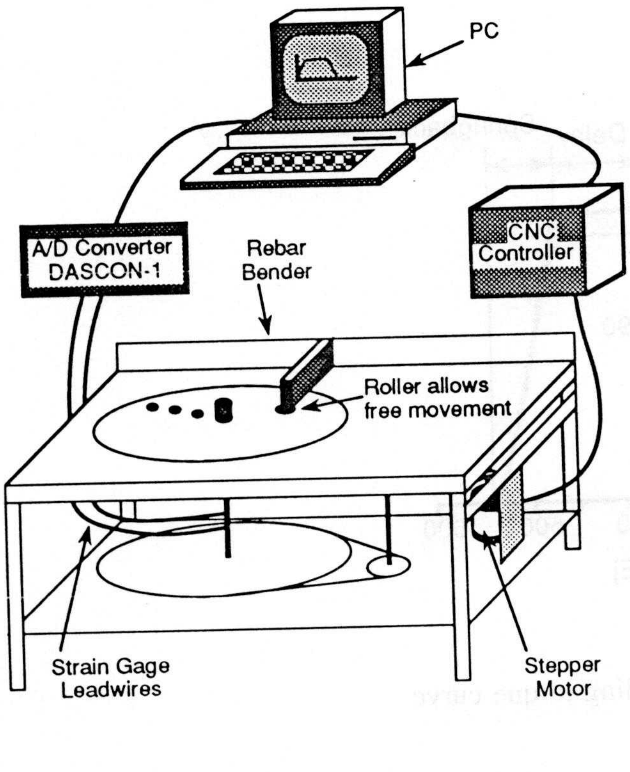

Figure 2. Schematic of ARB Hardware

The series of chains, sprockets, and axles make up the power transmission system for the rebar bender. One chain connects the motor shaft sprocket to a larger sprocket with the gear ratio of 9:112 which in turn drives a smaller sprocket. A second chain then allows this sprocket to drive the bending axle with a 10:112 gear ratio and an angular speed that is 0.7% of the commanded motor speed.

Strain gages on the main shaft of the bender act as force sensors for measuring the torque applied during bending. A DASCON-1 analog/digital converter board, housed inside the computer, converts the analog signal from the strain gages into a digital signal readable by the computer. A control program for the system is written in Microsoft QuickBASIC Version 4.5.

4. PATTERN ANALYSIS FOR CONTROL

The success of a real-time controller for bending straight deformed bars lies in its ability to use sensory data to accurately predict and compensate for the springback. The value of the sensor data as an input for control lies in the pattern information that can be extracted from it. Since the bending of rebar requires a manipulator which is able to provide rotational displacement, only the bending torque seems to provide useful sensory data. An example of bending torque data collected with ARB is shown in Figure 3.

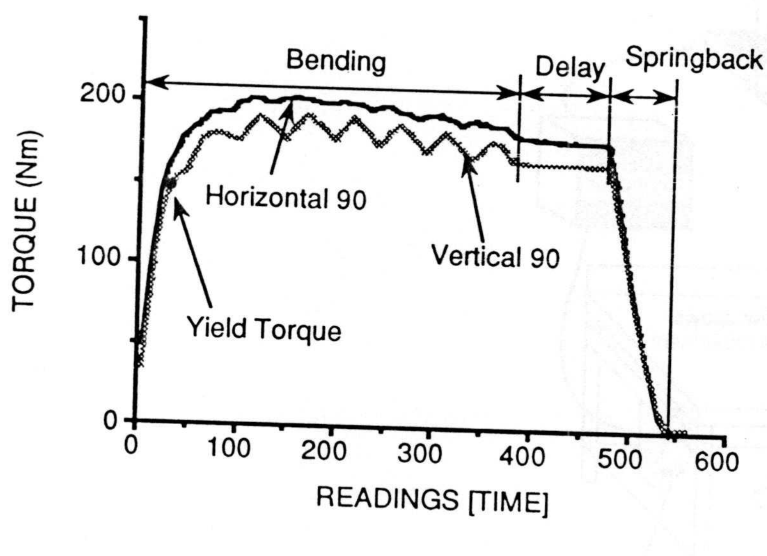

Figure 3. Fundamental features of the bending torque curve

Figure 3 depicts bending torque curves from two 90 degree bends made on one sample of rebar. One bend was made with the longitudinal ribs oriented vertically and the other horizontally (see Figure 1). This curve can be analyzed using the decision-theoretic approach to pattern recognition, wherein characteristic measurements or features are extracted from the input for classification and decision making [4]. Signature features of the bending torque curve can reveal valuable information about a specific rebar which can be used with rules for adaptive control.

Both example curves exhibit a linear increase in the start-up of the bending phase. After reaching a *yield torque*, the curve begins to level off with a gradually decreasing slope resembling the shape of a stress-strain curve. The bending phase is followed by a delay period during which the bender stops before returning to the start position. The final segment is the springback phase where a sharp decline in torque occurs. The amount of overbend necessary to compensate for the springback is related to the length and slope of the springback portion of the curve. The controller, monitoring and commanding the bender, must have a deep understanding of the factors and functions linking material properties with measurable operational data (e.g., torque) and the final outcome of the operation (e.g., bend angle).

Further examination of the bending torque curves in Figure 3 reveals valuable information about the rebar sample. It is clearly demonstrated that the amount of applied torque necessary to bend a bar with horizontally oriented longitudinal ribs (i.e., higher moment of inertia) is greater than the torque required for the same bar with a vertical orientation. The most distinct difference, however, is the smoothness of the horizontal curve relative to the jaggedness of the vertical curve. The peaks and valleys observed on the vertical curve are the result of encounters with the crosswise deformations on the surface of the rebar as it moves during bending. The longitudinal ribs provide a smoother translation of the rebar when it is oriented horizontally.

Figure 4 illustrates the types of features that can be analyzed from the bending torque curve data in addition to the rebar orientation. The features that may be used for predicting springback include an elastic torque modulus or slope from the purely elastic region of bending, the yield torque that can be identified using an offset criterion, and the maximum torque (average maximum torque in the case of a vertical orientation). Information that may be used in a feedback loop for recalibration or adjustment of control laws includes the range of the springback portion of the curve or the slope(s) of this portion of the curve. This portion of the curve has been divided into segments for slope calculations because it has been observed that the slope of the springback segment is not constant. It is possible that the changing slope may be due in part to a relaxation in the mechanical system of the rebar bender.

In order to establish links between the measurable features of the bending torque curve and the springback, torque data from numerous bend tests were collected and springback measurements were recorded. The torque data were fed into a data analysis program that was designed to process the data and extract values for the features of the bending torque curve. These feature values were then correlated with the corresponding springback measurements in order that the relationships between the feature values and the springback of the rebar may be studied. A scatter plot of one such correlation is illustrated in Figure 5.

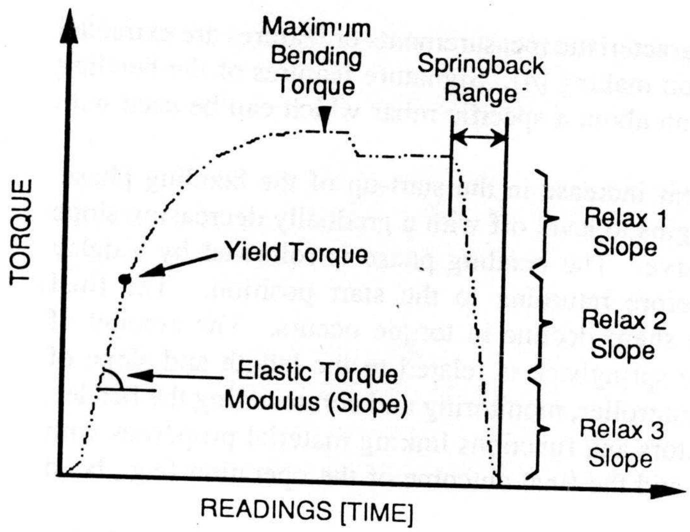

Figure 4. Feature based data points for predicting springback

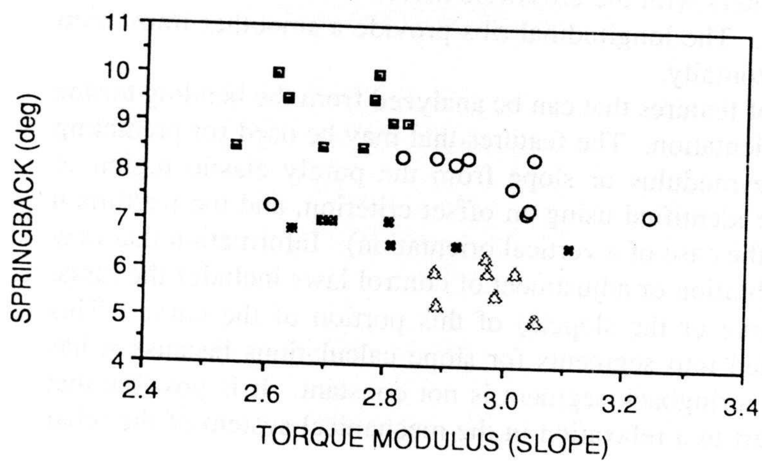

Figure 5. Sample data from bending tests

Figure 5 shows a plot of the elastic torque modulus (slope) versus springback for one batch of rebar. The data sets are described by combinations of the bend angle (45 or 90 degrees) and the orientation of the longitudinal ribs (horizontal or vertical) as illustrated above (see Figure 1). It is apparent that the degree of the bend angle has a significance since the springback for the 90 degree bend is consistently larger than for the 45 degree bend. Also, at any bend angle, an horizontal orientation of the longitudinal ribs results in a lower springback which corresponds to a higher elastic torque modulus. Finally, the grouping of the data by bend angle seems to reveal a trend with a downward slope. Such data sets as this are now being analyzed statistically for multiple batches of steel so that true patterns may be established. These patterns will subsequently be used to formulate control laws for a real-time controller.

5. CONTROL MODEL CONCEPTS

A primary task in creating a scheme for automating the fabrication process is the modeling of both the machine (manipulator) and the material (object). An exact model of the interaction between the manipulator and its environment is necessary for achieving precision in commanding accurately the manipulator's motions. The concepts of admittance, impedance, and impedance control [5, 6, 7] have been used in applications with similarly complex models where a manipulator has mechanical contact with the workpiece.

As explained by Hogan [5], 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 the use of such 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 [5]. Based on these definitions the rebar bender acts as the impedance while the rebar itself can be modelled as an admittance.

Rebar bending is a task requiring physical contact in which both 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 which complicate the task of control [8]. The rebar bender compliance may be viewed as a mass-spring-dashpot system [7], that is, having inertia, damping, and stiffness parameters. In order to develop the necessary control laws, the relationships between motion and deviations in observable measure have to be clearly understood. The two critical measures in rebar bending are the bending torque and the springback.

6. SUMMARY

The robotic bending of straight rebar has the potential to dramatically impact the production and placement of steel reinforcing bars through accurate, just-in-time fabrication. Real-time adaptive control for rebar bending relies upon the establishment of control laws based upon models that accurately describe the rebar bender and the rebar. This paper has presented the type of data used for the development of a model for the rebar and has described the prototype automated rebar bender that is being used to obtain this data and to conduct experiments to test control laws developed from this data. Initial analysis of pattern information reveals a strong potential for establishing the control laws needed to have intelligent control for accurate bending through springback compensation.

7. REFERENCES

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