PROCESS DRIVEN AUTOMATED REBAR BENDING

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ABSTRACT

This paper will present a new concept for rebar bending, which is based on merging the advantages provided by integrating electronic sensors, computer controlled motors, and data communication with a personal computer. The complexity of predicting the springback of rebar through pattern recognition and impedance control are also being discussed. It is shown how such a system could reduce costs associated with trucking, handling, site storage, and wasted time due to short shipments, late deliveries, change orders, and inappropriate batching of the reinforcement bars.

Keywords: CAD/CAM, pattern recognition, automation, control, rebar bending

1. INTRODUCTION

Computer integrated construction, which relies on the sharing of data and information, faces many obstacles which reach from legal problems to the creation of standards for data communication. The promise of using design data for the actual production of building elements or even building material, such as reinforcement bars (rebar), has intrigued the author to investigate the problem of automating the actual bending of the bars.

While concrete itself is being researched and production of concrete more and more automated, the fabrication of reinforcement steel received little attention from researchers in the United States. If the intelligent and robotic fabrication of rebar could be accomplished, the subsequent benefits could have a significant effect on how concrete construction is organized and managed. For one, the flexibility of a computer controlled rebar bending system would allow the bending of bars not in batches according to type but rather in batches according to their placement position. Such an approach, however, would require the use of an intelligent process planner to specify the sequence of the rebar placement before the rebar is ordered.

The bending of straight reinforcement bars is still mainly done with hand operated machines. The controls require humans to set turning angles and to select the appropriate pegs and pins for the turning table. The basic reason for this, at least in the United States, is the fact that the steel is not sufficiently standardized to guarantee a standard mechanical behavior of the bars when bent. In fact, the possible variations in steel bridleness require the machine operator to pretest every new batch, if it can be identified, in order to determine if the steel would not actually break during bending. The correction for the actual springback is also a very important issue to achieve rebar bends which meet specifications.

In the following sections, the traditional approach to concrete reinforcement fabrication will be discussed briefly before introducing a CAD-integrated concept, automated process planning concepts, and a proposed concept for robotized bending.

2. TRADITIONAL REBAR SUPPLY

The fabrication of concrete reinfocement generally goes through the process of engineering design, detailing, shopdrawing review, fabrication, shipment, on site storage, and finally placement in the concrete form. These activities follow each other sequentially with a lead time between ordering the rebar from fabricators and placement of the bars. Short shipment, late deliveries, and other types of errors are many times caused by change orders and lack of proper communication between engineers, contractors, and fabricators resulting in "quick-fix" solutions.

For example, rebar is often cannabalized from other shipments and cut to fit with torches, further aggravating the problem. One inherent problem is the required lead time, a time during which delivery, construction schedule changes or change orders occur. Should a change order occur after the rebar has been fabricated, little can be done other than fabricate additional bars. One solution to the inherent problem of changes during or after fabrication is to postpone the fabrication until the time immediately preceding placement. This would allow greater flexibility and require zero lead time between order and delivery of fabricated bars.

3. THE ZERO LEAD TIME CONCEPT

The elimination of the lead time for rebar order requires that the cutting and bending of rebar directly precedes placement. This requirement has implications on the logistics as well as on the fabrication itself. First, the fabrication of rebars needs to be at the location of placement, and the rate of fabrication has to be approximately equal to the rate of placement. Figure 1 provides a time based comparison of the zero lead time concept vs/ the traditional approach.

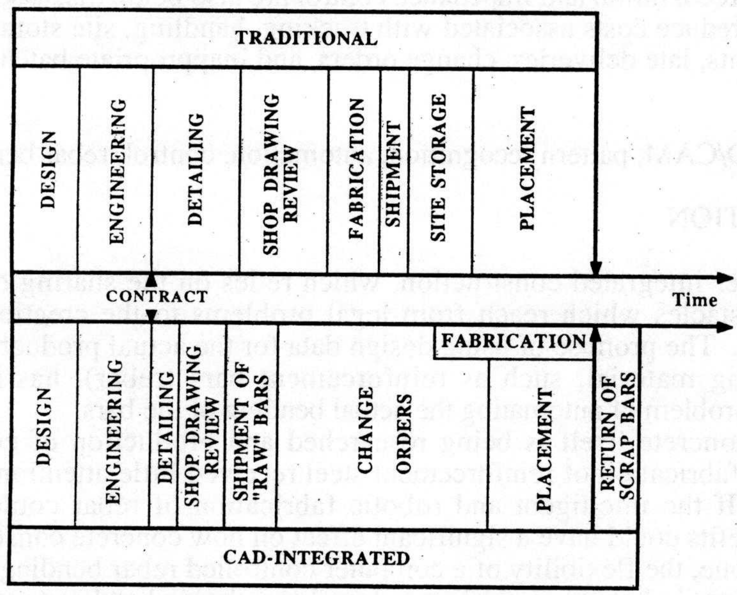

Figure 1. Comparison of Rebar Fabrication Schemes

The zero lead time production concept is nothing new. On site prefabrication methods, just-in-time (JIT) and Kanban related materials handling (McLeod 1986) have proven the effectiveness of this approach leading to low inventories and more efficient production. In respect to rebar fabrication, the zero lead time concept has only been used on a limited basis mainly because of the high cost in acquiring bending machines and highly competitive fabrication plants.

The advent of computer controlled machines, CAD-integrated planning systems, and reliable data collection and communicaton capabilities have brought with them new opportunities for the fabrication of rebar. The corner stone of a potentially new concept is the integration of design with fabrication by the means of electronic data sharing. The premise of computer controlled rebar bending is that engineering design data can be downloaded into a detailing program which determines the number, size, type, and required lengths of rebar shapes. From such a database, barlists and shopdrawings can be generated on the CAD system. This same database could be sorted or changed as required prior to fabrication to respond to change orders or last minute changes in the construction sequence. From the barlist database, only the bars needed for a particular pour would be fabricated and bundled according to the process plan.

4. AUTOMATED PROCESS PLANNING

While CAD or CADD has brought many benefits to design oriented firms, a vast amount of ever more significant opportunities have not been tapped into. One such example is the use of the dumb CAD representation of a rebar detail to drive a machine which is able to produce a design which meets all the specifications. This concept is central in computer-aided manufacturing. (Bernold and Reinhart 1990) Automated process planning of rebar fabrication should allow the automatic evaluation of a CAD represented rebar design, with the objective to develop a production schedule which is based on the sequence the rebar will be actually placed into the formwork. In addition, the process plan would provide instructions to the computer controlled machine on how to cut and bend each bar. Figure 2 provides a sequence of a typical set of generic instructions and their results.

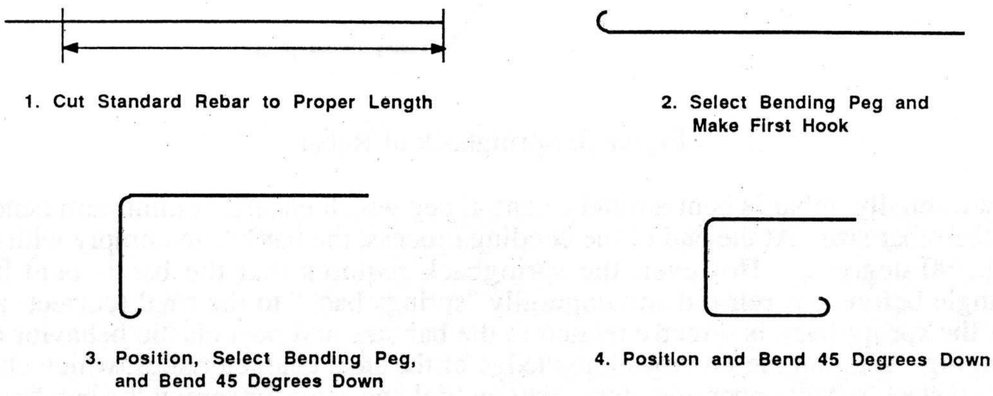

Figure 2. Task Sequence of a Rebar Bending Process

The different approaches to automated process planning has been addressed in the literature (Bernold and Reinhart 1990, Nau 1987, Rembold et al., 1985). Process plans have to be translated into instructions to the machine(s) to cause physical motions and movements. Intelligent machines, which are able to adjust to changing situations, not only require commands for performing individual tasks but also the intelligence to interpret data collected real time about the changing conditions in the work cell or the hardware itself (e.g. forces and torques). Feed-forward and feed-back loops are two of the basic concepts used for building control systems as an integral part of robotic machine. The question of control in respect to rebar bending will be the main issue discussed in the remainder of this paper.

5. AUTOMATED CONTROL FOR REBAR BENDING

The probabilistic and dynamic interaction between a machine-tool and the material to be processed create special problems for control. Generally three basic force and motion dependent control structures are discussed in the literature: a) position control, 2) force or compliance control, and 3) impedance control. (Hogan 1985, Paul 1987, Goldenberg 1988) The goal of the three approaches is to model the movement of manipulators for the purpose of automatic control. All three control structures have been used in the industry for specific purposes. The selection of the best control structure for rebar bending depends in particular on the interaction between the tool and the rebar during the bending process. The correction for springback is, in fact, the most critical issue in this respect. A control system which is able to provide accurate compensations for springback has to be able to predict accurately the springback prior to the completion of the actual bending motion in order to properly adjust the tool path real time.

5.1 Compensation for Springback

Due to the material properties of steel, the bending of bars results in an elastic deformation after the completion of the bend, called springback. Figure 3 shows the effect of this phenomenon.

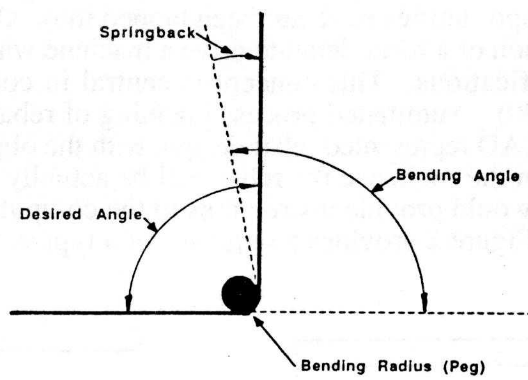

Figure 3. Springback of Rebar

Traditionally, rebar is bent around a central peg which ensures a minimum bending radius related to the rebar size. At the end of the bending process, the bar has to comply with the desired angle (e.g., 90 degrees). However, the springback requires that the bar is bent beyond the required angle before it is relaxed and hopefully "springs back" to the final (correct) angle. The amount of the spring-back is directly related to the bar size and post elastic behavior of the steel during bending. Without the previous knowledge of the steel characteristics, which changes with each batch of steel, rebar bender operators relay on trial and error for setting the bending machine.

Impedance control incorporates the necessary principles needed for springback control, because it considers both the tool (manipulators) and the material as part of one system. The logic as presented by Hogan (1985) is: "The most important consequence of dynamic interaction between two physical systems is that one must physically complement the other. Along any degree of freedom, if one is an impedance, the other must be an admittance and vice versa." In the case of the rebar bender, the bender can be defined as an impedance translating motion into force, and the steel bar is the admittance which accepts force and reacts with change in position.

5.2 Pattern Recognition for Bending Control

Human beings depend on pattern recognition in their daily lives, even reading is in essence pattern recognition. The central objective of automatic pattern recognition is to use the capabilities of fast machines to observe the environment and thus to support humans in detecting and recognizing problems, or robots in performing their tasks.

Many methods for the analysis of digital signals have been proposed in the past: "The many different mathematical techniques used to solve pattern recognition problems may be grouped into two general approaches, namely the decision - theoretic (or statistical) approach and the syntactic (or linguistic) approach." (Fu 1980) The first approach relies on identifying characteristic measurements or features which supposed to be invariant for proper identification. The syntactic method is geared toward describing the pattern in order to explain why a pattern was identified as such. The application of artificial intelligence principles prevails in the more recent utilization of pattern recognition. "..., signal analysis/pattern recognition expertise must be combined with domain specific heuristics to obtain the desired understanding. The domain-specific heuristics comprise the body of knowledge acquired by an experienced practitioner and consists of a series of clues to reduce ambiguities commonly encountered in signal interpretation tasks." (Dawant and Jansen 1988) For example, vision systems use artificial intelligence to assist in the analysis of complex images such as landscapes.

For the characterisation of steel reinforcement, a variety of patterns are already being used today. One of the most commonly used method for presenting mechanical properties is the stress-strain diagram (see Figure 4).

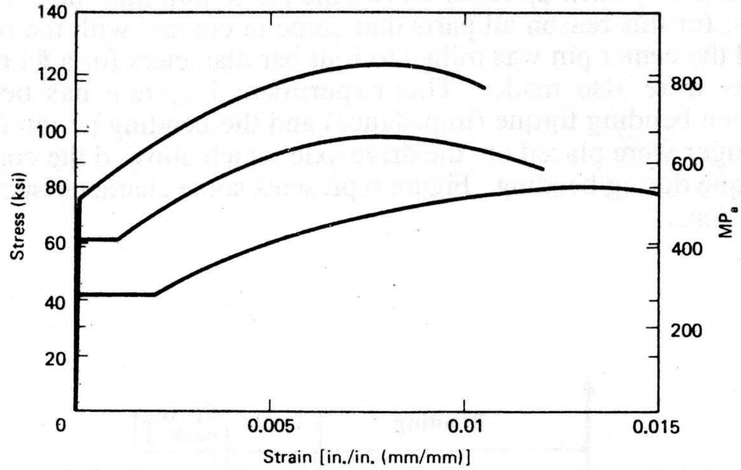

Figure 4. Typical Stress-Strain Diagrams for Various Steels

Principles of statistical and syntactic pattern recognition are used to identify points representing yield and ultimate strength. The stress-strain diagram is being generated through a destructive tension test and is available from the steel mill.

The mechanical behavior of the bar during bending is related to its elasticity, as well as its yield and ultimate strength. Thus, it could be possible to predict the springback of a particular rebar based on such information. However, since the steel is not uniform within one batch, a control system which is based on such measures could result in great variances of final bend degrees. In an ongoing research effort, within the Construction Automation Research Laboratory at North Carolina State University, it is sought to establish a pattern recognition scheme for real time strain interpretation. Figure 5 presents an experimental rebar bender in action.

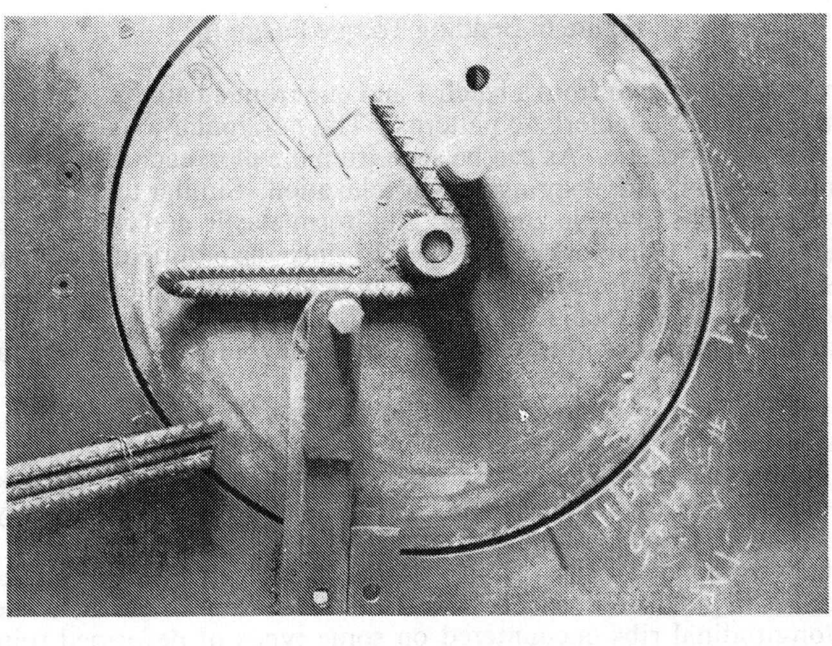

Figure 5. Experimental Rebar Bender

The basic elements of the bending machine are visible in Fig. 5. The center axle not only holds the circular plate in horizontal position but also provides the necessary torque to drive the bending pin. A stationary back up roller allows the bar to pull into the bend without introducing additional stresses; for this reason all parts that come in contact with the rebar are free to move. The sleeve around the center pin was milled to four bar diameters for a #4 rebar, other sleeves for different bar sizes were also made. This experimental system has been used to study the relationship between bending torque (impedance) and the bending action (admittance). For that purpose, strain gauges were placed on the drive axle which allowed the continuous measurement of the bending torque during bending. Figure 6 presents some characteristic torque diagrams from such experimental runs.

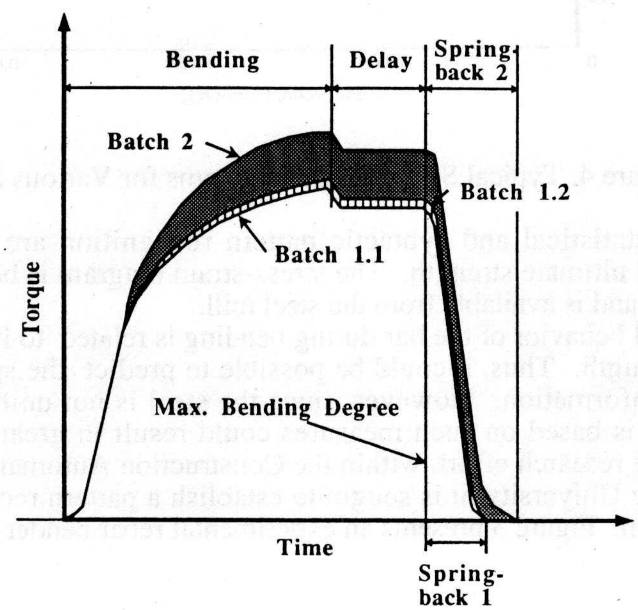

Figure 6. Bending Torque Diagrams

Three torque profiles, two from a batch 1 and one from a batch 2 , are being compared for the purpose of identifying characteristic patterns. The horizontal axis represents time and the vertical axis the amount of torque. As can be seen from the plot, each curve shows three distinct phases: 1) bending, 2) delay, and 3) springback or relaxation. Similar to the stress-strain diagram, the torques during bending show two zones of: a)uniform elastic deformation, and b) elastic and plastic deformation. Such a behavior can be expected since the deformation in the cross section(s) of the rebar does not happen uniformly but rather gradually, starting at the outer border. After a short delay, only used to create recognizable pattern points, the rotating motion is reversed. The relaxation results in a springback (discussed ealier) and eventually in a separation of tool and rebar.

The analysis and comparison of the diagrams shows that the bars from the two batches show differences in the necessary torque to achieve the required bending degree. A higher torque needed for bending the bar from batch 2 coincides also with a larger springback. Again, such a phenomenon could be expected since batch 2 seems to have to have higher yield and higher ultimate strength allowing larger elastic deformations.

The two bars from batch 1 show slight differences in the maximum torques. This could be the result of variances in yield strength. However, the real reason for the difference is the changed position of the longitudinal ribs encountered on some types of deformed reinforcement bars. Figure 7 shows deformed bars approved by ASTM.

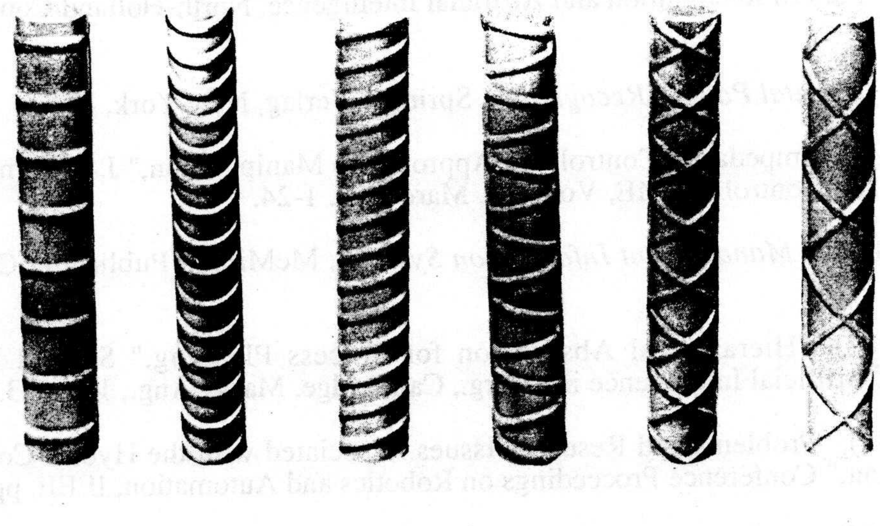

Figure 7. ASTM-Approved Deformed Bars

Batch 1 consisted of the type bars shown at the very right in Fig. 7. As can be seen in Fig. 5, the same bar was bend first with two longitudinal side ribs perpendicular to the rotating plate, and secondly, after a 90 degree rotation, parallel to the table (position of bar shown in Fig.5).

Experimental results show consistent patterns of torques which correlate with the amount of springback. Present work concentrates in fully understanding the mechanics of bending and the testing of a control system which utilizes both feed-forward and feed-back control loops.

6. SUMMARY

The industry has only scratched the surface of utilizing computers for design, engineering, construction, and maintenance of facilities. The presented paper describes one scenario in which contractors could use a CAD integrated reinforcement detailing system which is linked with robotized fabrication. Ideally, such a system could eliminate off-site detailing, shop drawing production, and fabrication.

Implementation of such a system depends on artificial intelligence and electronic sensing devices for real time control of the bending motion. The author has shown how principles of impedance control and pattern recognition could be utilized to provide the necessary elements to achieve such a goal. Results of laboratory experiments have established confidence that the proposed concept could actually work.

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