Placement-Oriented Design and Delivery of Concrete Reinforcement

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Abstract: The use of reinforced concrete in the United States is steadily increasing, and with it the need for designed and fabricated reinforcing bars (rebar). Traditionally, the detailing of the rebar is done by the fabricator, who is required to have the shop drawings approved by the civil engineer in charge of the structural design. Subsequently, the rebar is fabricated and shipped to the site where an independent subcontractor places the rebar according to the detail design. Research has shown that the delivery of construction material is strongly related to the productivity of construction processes, such as laying rebar. However, traditional rebar fabrication and shipment is geared towards minimizing the set-up time of the rebar bending machine. As a result, rebar is cut, bent, and bundled according to shape and size without considering the sequence of placing the bars. This paper presents an alternative way to design and deliver concrete reinforcement that is based on computer integration and feature-based design concept. Detailing data generated with CAD software is used to create rebar placement plans, shipping schedules, and assignments of lay-down area on the construction site. Based on experiences with the application of the system, steps necessary for its implementation are discussed.

Introduction

Traditionally, the installation of concrete reinforcement is sequentially organized into four phases: (1) Ordering; (2) approval; (3) fabrication and shipment; and (4) placement. On a more detailed level, the ordering and approval phases include engineering design, detailing, preparation of shop drawings, and approval of shop drawings. The main purpose of rebar fabrication in a plant and subsequent shipment is to simplify field assembly by prefabricating the individual bars in a fixed plant environment. The reinforcing bars (rebar) are delivered to the job site and checked for compliance with approved shop drawings in quantity, dimension, and other requirements. Short shipment or fabrication error, if any, is reported to the subcontractor or supplier for proper rectification or correction. This rectification or correction procedure often requires a considerable amount of time and causes additional cost.

The efficiency of the installation, or placement, of cut and bent rebar depends on how effectively the delivery is organized. Thus, site storage and shake-out require careful planning to facilitate the efficient assembly of rebar in place or in prefabricated cages. The importance of the proper laydown areas has been addressed in literature (Thomas et al. 1989). Unfortunately, in today's construction, the planning and coordination of shipment, and shake-out operations receive very little attention. A detailer usually develops installation plans that depict the sequence of placing rebar into the concrete form. However, the actual placement is not planned and controlled

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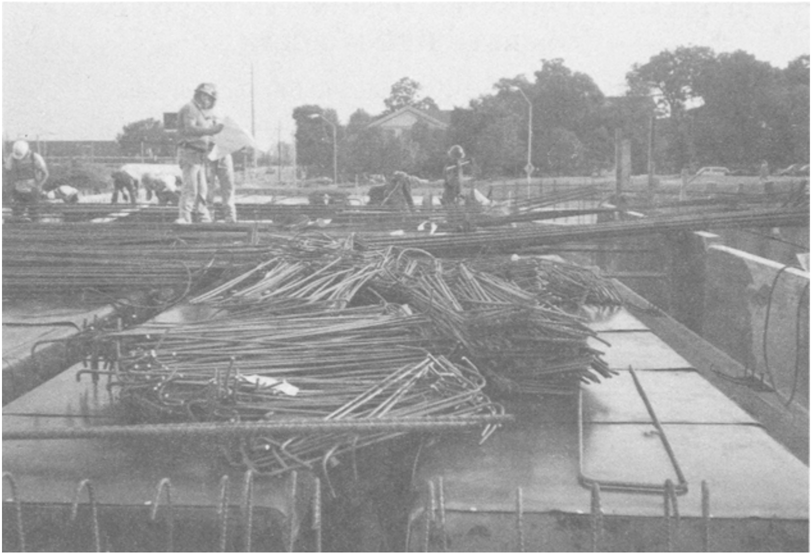

FIG. 1. Traditional Laydown and Placement of Rebar

by the detailer. As a consequence, rebar of the same type and size is fabricated and bundled without considering the requirement for sequential placement. Fig. 1 presents the result of the traditional way of bundling and random organization of the fabricated rebar in the lay-down area on the concrete formwork.

In Fig. 1, longitudinal bars of similar size and type for six beams are bundled together. The foreman is studying the drawings to find the remaining bars for the first beam for which placement has already started. The time and resources for searching out and pulling the needed bars from underneath other bars is costly. Thus, to ensure efficient installation and to avoid rehandling, the plan for fabrication and shipment should be based on the sequence of rebar placement. In particular, the rebar should be bundled and delivered according to the order of assembly.

Organizing delivery of rebar according to their sequential placement and staging may require special bundling at the fabrication shop for certain structural elements. For example, smaller (micro) bundles with sets of straight and bent bars of a beam could be tied together into a bigger (macro) bundle for shop lift and subsequent staging at the job site. Special bundling will create more work in the shop, caused by the additional time needed for specialized bundling. On the other hand, substantial time could be saved in the field for assembly operation. Significant difference in the hourly rate between the fabrication-shop worker and the field ironworker plays a very important role. The approximate hourly wages of steel workers in North Carolina are $10 in the shop and $25 in the field. Thus, by shifting 1 h of work from the site to the shop will account for $15 of overall cost saving.

A basic requirement to achieve a placement-oriented (driven) delivery is the availability of a placement plan. A CAD-integrated process-planning system using artificial intelligence (AI) or a human expert could assist the detailer in creating rebar designs that are able to represent the order of

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assembly, i.e., sequential placement. A placement plan that depicts the order of assembly could be the basis for subsequent operations, such as the unloading of delivery trucks on site.

Intelligent process planning has as its objective the artificial creation of operational plans. The following section will discuss briefly the key elements of intelligent process planning.

Approaches to Intelligent Process Planning

Process planning, as defined in the industrial engineering application, entails the preparation of a detailed plan for the production of a piece, part, or assembly. According to Ansaldi et al. (1989), "Process plans consist of sequential lists of individual manufacturing operations with all relevant associated information necessary to produce a part in a certain manufacturing facility." The same authors state that recent developments in the manufacturing industries are aimed at an intelligent process-planning system that would integrate design and production data for generating useable process plans. In the envisioned system, CAD representation of a part or object would be used to provide input data to the process-planning system, eliminating the need for human intervention to translating the drawing into a suitable form for automatic processing. Despite significant efforts to develop process-planning systems using different methodologies and formalism, the manufacturing industry has yet to develop a system that will fulfill this ultimate objective of intelligent process planning. Existing automated process-planning systems can be classified into variant and generative process planning (Chang and Wysk 1985).

A variant process-planning system uses key features of the product in identifying existing plans in a data base. When a new product is defined, the system searches the data base to find a predefined process plan based on the similarity of key features. Modification to satisfy nonstandardized requirements are performed by human planners.

In the generative process planning system, plans are generated automatically for a new product without referring to existing plans. The main drawback of this system is the difficulties in formalizing the declarative and procedural knowledge in a problem (Chang and Wysk 1985).

A knowledge-based process planning system (PLANEX) for construction and manufacturing was developed to overcome the difficulties of expressing the heuristic that is commonly used by human planners (Zozaya-Gorostiza et al. 1989). The development of the system can be regarded as a step forward in automating process planning, however, the system requires considerable human interaction.

Computerized Rebar Placement Planner (CRPP)

The process of placement, which includes the tying of the bars, is basically an assembly operation with individual or set(s) of bars. The proper sequencing for placing the bars has to be based on the requirements set forth by the assembly process on a macro as well as on a micro level. For example, higher or macro-level planning decisions relate to the strategy of where to start and where to end. Lower or micro-level decisions relate to which bar comes first, second, and so forth. The identification of an optimal lay-down, or staging location for bundles, or sets of rebar play an important role in assembly operation. According to Bernold and Reinhart (1990), an intelligent process-planning system could be instrumental in handling such practical problems without human involvement.

Fig. 2 presents the schematic of the CRPP architecture, which implemented the concepts of both intelligent and manual process planning. Rebar detailing utilizing a CAD system is supported by a rebar feature library. The feature library contains standard rebar configurations. Two variables of a rebar include its size and the lengths of different bar sections. On the other hand, the shape of a rebar (e.g., closed stirrup) is an important feature that is directly related to the rebar fabrication and, possibly, to the sequence in which the rebar is placed into the formwork. In the CRPP, the designer is able to pick any standard bar from the library and insert it into the design drawing. Frame-based attribute lists enable the designer to specify size, lengths of different sections, and so forth. Upon completion of the feature-oriented rebar design, CAD data is made available to the data-base-man-

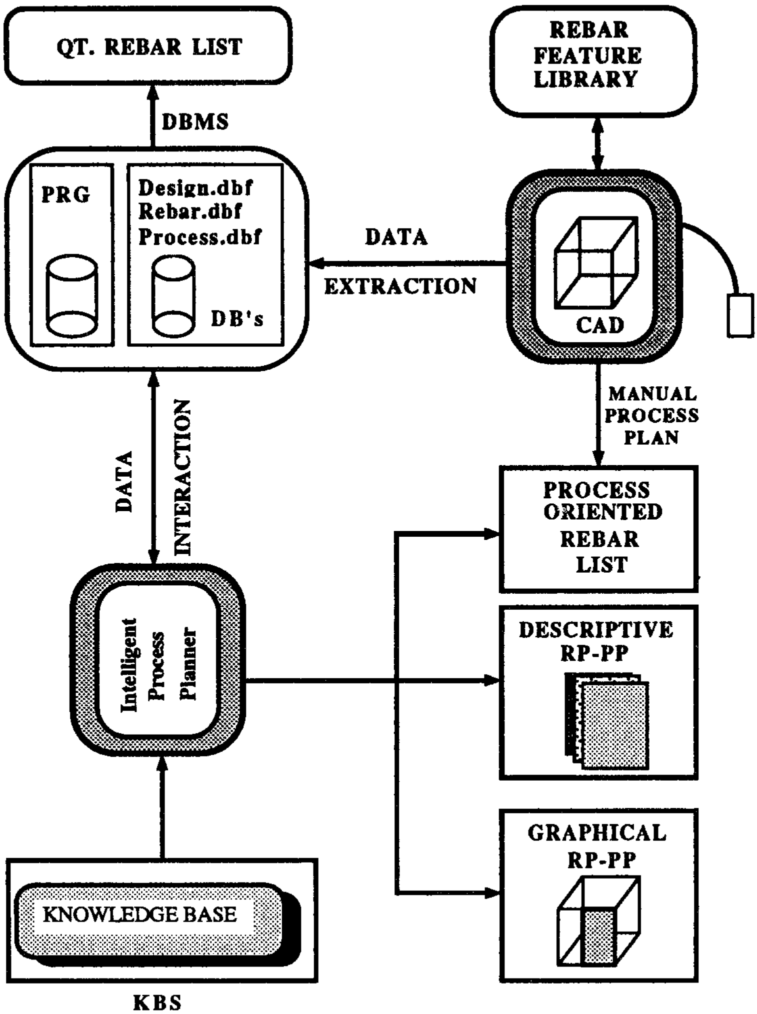

FIG. 2. Architecture of Computerized Rebar Placement Planner (CRPP)

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agement system (DBMS), as shown in the CRPP model in Fig. 2. The DBMS is able to generate bar lists, which are used to order bars. A typical bar list is shown in Appendix I. In this bar list, dimensions A-G correspond to standard bar bend dimensions. In the CRPP, CAD representation of the rebar details is stored in a rebar data base (Rebar.dbf). The DBMS is also used to generate the necessary input to an intelligent process planner (PP). The CAD data is massaged and reorganized within the DBMS for use in the process planning system. The output of PP are placement plans created with the support of a knowledge base. As shown in Fig. 2, CRPP also supports a human expert to create a placement plan manually (without the use of PP). The manual planning is accomplished by labeling the sequence of placement of individual or set of bars using the tools provided within the CAD system. In this case, a human planner sequences the placement by labeling the individual or set of bars with ascending numbers. Thus, when data is extracted from CAD, the list of rebar shows not only sizes, lengths, and so forth, but also their position in the placement sequence. The sequential rebar placement can also be graphically represented by three-dimensional (3D) CAD drawings.

The following section discusses the two basic planning models developed for the CRPP.

Search Trees

As mentioned earlier, the placement and tying of rebar is an assembly-type operation. Thus, structures are needed to create a layout of all the necessary elements in such a way that an intelligent system is able to search and find feasible sequences for assembly. Fig. 3 presents the first search tree that enables the physical organization of the rebar. The hierarchical breakdown structure for concrete reinforcement of a building utilizes build-

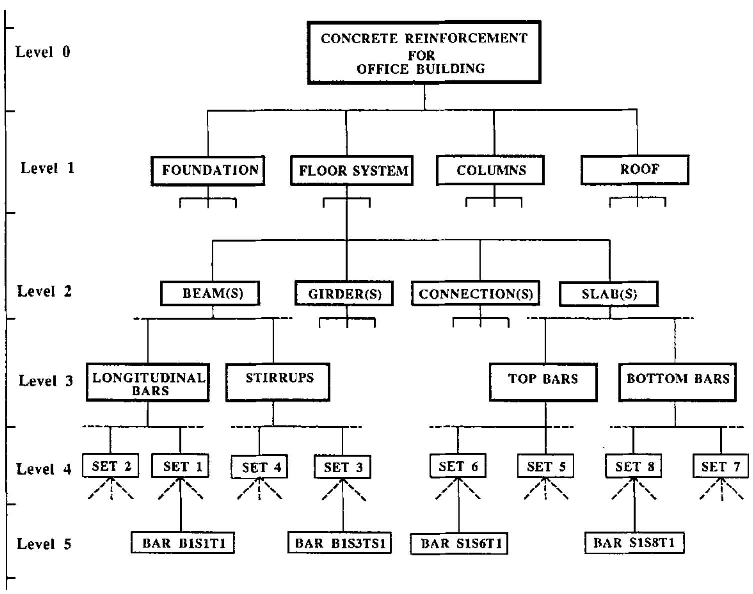

FIG. 3. Feature-Based Tree Structure of Concrete Reinforcement

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ing as well as rebar features to create a tree-like decomposition of the total rebar system. The individual bars at level 5 of the hierarchical tree structure represent the physical bar elements. Each element is identified with a notation (e.g., B1S3TS1). The individual rebar elements can be grouped together into set(s) based on the commonality of certain features (e.g., type/shape). The bars or set(s) collectively represent a subassembly at level 3 (e.g., STIRRUPS). For example, the individual stirrups of type TS1 combined into SET 3 (S3), which belongs to BEAM 1 (B1). Thus, the address of the individual bar is B1S3TS1.

The hierarchical structure for organizing the concrete reinforcement is not sufficient for the intelligent planning of the assembly sequence. A second

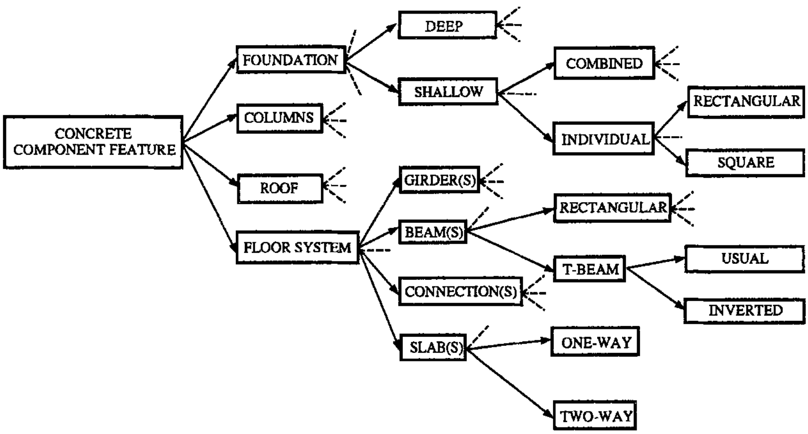

FIG. 4. Process-Oriented Tree Structure of Rebar Placement

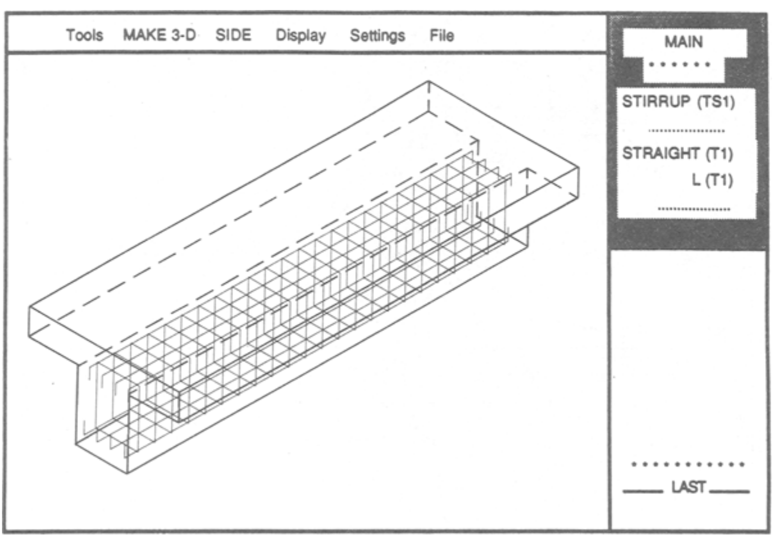

FIG. 5. Feature-Based Rebar Design of Beam in AutoCAD

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structure has been established to organize the placement operations according to critical features of the concrete elements and the rebar design. A maximum of four node levels are required for this structure, presented in Fig. 4. For example, a floor system can be broken down into classes of beams, slabs, girders, and connections. A beam class can further be broken down into subclasses of T-beams, rectangular beams, and so forth. The main purpose of this hierarchical breakdown is to represent the concrete elements as structured objects to facilitate the search procedures necessary for creating placement plans artificially. For example, an individual or set(s) of bars (e.g., longitudinal bars and stirrups) collectively represent the reinforcement for a beam, as shown in Fig. 5. The two decomposition models will enable the beam reinforcement to be methodically arranged so that it can be understood by the intelligent process planner.

The classification of both tree structures presented in Figs. 3 and 4, are linked through a common nomenclature. For example, the descriptor BEAM(S) appears in both structures, and therefore provides a natural connector between the two trees. In fact, the developed system exploits this linkage.

Integration of Off-the-Shelf Software

The CRPP was implemented by integrating LEVEL5 OBJECT (an object-oriented data base with a linked rule base) running under Microsoft Windows, AutoCAD (release 11), and dBASE III PLUS. AutoLISP programs were written to support the feature-based detail design, as shown in Fig. 5. AutoLISP is an implementation of the LISP programming language embedded within the AutoCAD package. AutoLISP adheres most closely to the syntax and conventions of common LISP, but AutoLISP is a small subset and has many additional functions that are specific to AutoCAD. Using AutoLISP, it is possible to add custom commands to AutoCAD, extending it to meet specific requirements. In Fig. 5, longitudinal bars STRAIGHT T1 and L(T1), as well as stirrup TS1 from the CAD library, were utilized to create the drawing. Each rebar element is modeled as an individual object with attributes such as size and bar identity code. In addition, other topological and descriptive attributes required for the object's complete description are also attached to the individual rebar element. The attribute values are provided by the user while inserting the rebar elements from the standard feature library into the CAD drawing. Data that is transferred to the PP include feature class, subcomponent, subcomponent type, weight, assembly, bar_spec, set, orientation, and location. The presented tree structures and the related organization of common data are needed to enable the PP to develop the desired plans based on expert knowledge stored in knowledge bases.

CRPP Knowledge Bases

Placement of rebar is based on hard and soft operational rules, which depend heavily on the features of the rebar and the concrete components and subcomponents. For instance, a usual T-beam (slab on top of rectangular section) requires a different rebar placement plan than an inverted T-beam. CRPP uses the concept of object-oriented programming (OOP) by breaking down concrete component features into hierarchically structured objects. The knowledge about the sequential placement of rebar that is required for assembly of a particular subcomponent (e.g., T-BEAM) is organized in a

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knowledge base. The knowledge base of CRPP is organized as a collection of rule bases for macro- and micro-level planning. A bottom-up forward-chaining rule-based approach is used to develop rebar placement plans for a building structure. For example, the following rule is able to identify the sequence for placing rebar in a usual T-beam:

IF
  Feature_class = BEAMS AND
  Sub_component = T-BEAM AND
  Sub_component_Type = USUAL AND
  Bar_spec = STIR AND
  Assembly = IN-PLACE
THEN Sequence# 1 = STIR AND
  Sequence# 2 = BOT AND
  Sequence# 3 = TOP

This rule is modeled using the process hierarchy presented in Fig. 4, the features of the rebar itself, and common construction practice observed on site. Generally, closed stirrups (STIR) are placed first into the formwork of a T-beam; this step is shown in the conclusion clause of this rule as Sequence# 1 = STIR. In the second step, bottom longitudinal bars (BOT) are fed into the stirrups, spaced, and tied. Fig. 6 presents the completion of the second step of rebar placement for this beam. Next, the top longitudinal bars are fed into the stirrups, spaced, and tied to complete the rebar placement for a usual T-beam. As mentioned earlier, data-driven forward-chaining rule bases have been utilized to create rebar placement plans. The software package LEVEL5 OBJECT facilitates the search for the antecedents of rules. For example, when antecedents for a rule become true, it will fire, and the actions are dictated by the consequents of the rule. One example is the sequence for placement of rebar in the T-beam presented as the conclusion clause.

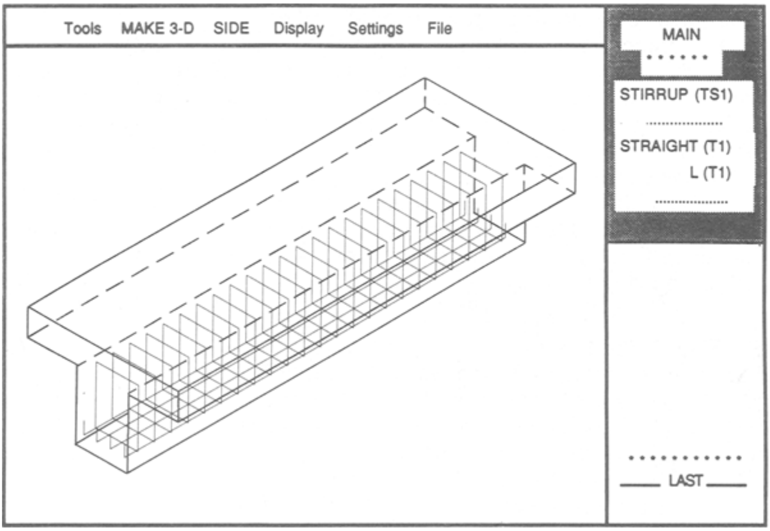

FIG. 6. Completion of Step 2 (Sequence# 2) of Rebar Placement for Beam

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AFTER PROCESS PLANNING ACTION											
BEFORE PROCESS PLANNING ACTION									REBAR PLACEMENT SEQUENCE#	BUNDLE CODE	LAYDOWN AREA LOCATION
FEATURE CLASS	SUB COMPONENT	SUB_COMP. TYPE	BAR_SPEC	SET	WEIGHT	ORIENTA-TION	LOCATION	ASSEMBLY			
SHALLOW FOUNDA-TION	IND. COLUMN FOOTING	RECTAN	BL1	1	0.40	0,0	C1	IN-PLACE	1.0	F.C1.1.1.0	C1.1
SHALLOW FOUNDA-TION	IND. COLUMN FOOTING	RECTAN	BL2	2	0.30	90,0	C1	IN-PLACE	2.0	F.C1.2.2.0	C1.2
....	....	....	....	....	....	....	....	......	....	....	.....
SHALLOW FOUNDA-TION	IND. COLUMN FOOTING	RECTAN	TL1	3	0.40	0,0	C1	IN-PLACE	4.0	F.C1.1.4.0	C1.1
....	....	....	....	....	....	....	....	....	....	....	.....
BEAMS	T-BEAM	USUAL	STIR	60	0.40	-	B1	IN-PLACE	21.0	B.B1.1.21	B1.1
BEAMS	T-BEAM	USUAL	BOT	61	0.80	0,0	B1	IN-PLACE	22.0	B.B1.1.22	B1.1
BEAMS	T-BEAM	USUAL	TOP	62	0.70	0,0	B1	IN-PLACE	23.0	B.B1.1.23	B1.1
....	....	....	....	....	....	....	....	....	....	....	.....

FIG. 7. Data Structure before and after Intelligent Process Planning

The result of a successful sequencing of the rebar for a T-beam is shown in Fig. 7. As depicted, the PP assigned the number 21 to the rebar placement sequence# (PS#) field of STIR, number 22 to PS# of BOT and number 23 to PS# of TOP. A counter is used to create continuous sequence numbers for rebar placement.

The detail of the created placement plan offers an excellent opportunity to organize the delivery of the fabricated rebar according to the assembly sequence. As mentioned earlier, rebar is traditionally bundled depending upon size and shape, and stored in a haphazard manner in the site laydown, or staging area. This bundling method and on-site storage does not take into account the order of assembly. One alternative approach to this traditional method is to bundle and deliver set(s) of rebar according to the placement plan. For example, rebar for an individual column footing with only two layers of reinforcement for the bottom mesh could be bundled separately, each bundle consisting of the rebar for one layer. During unloading, the set(s) of bundled rebar could be directed to predesignated laydown, or staging areas to minimize additional handling. Thus, placement planning, bundling, and on-site storage can be linked by further using the design data stored in the computer. As a consequence, rebar placement planning could provide not only sequence, but also precise laydown, staging, and bundling schemes of set(s) of bars.

To take advantage of this opportunity, rule bases have been established for establishing bundling and storage assignments. The bundling procedure has to consider several conditions and constraints. For example, the available rigging machinery will constrain the capacity to be lifted. On the other hand, sets of rebar belonging to the same building element (e.g., column footing) should be combined into one lift to allow minimum rigging time during unloading. Available storage areas, described using the CAD system, control in many ways the bundling scheme, which also includes combinations

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of several sets of bars with a common shape into macro bundles. A macro bundle may consist of several individual (micro) bundles, each a single set of bars. Overall, the objective of a bundling rule base is to create bundles that minimize the rigging and assembly time by supplying the bars according to the laying sequence during the final placement. In other words, rebar that is needed next should always be immediately accessible. Fig. 7 includes the results of such a planning task. However, the hand-controlled bending of straight bars at the fabrication shop requires set-up time before bending every new set of bars. To minimize these costs, while also putting together micro bundles as subsets of a larger set (e.g., 5 bars from a total of 20 bars), intermediate storage areas at a loading dock are needed. Thus, careful planning and organization of the loading operation will be crucial to minimize the cost of fabrication and shipment. However, the improved planning and the creation of macro bundles serves as a checking instrument for shipment. Thus, the alternative strategy for rebar delivery provides a better way of checking against short shipment.

The laydown area for BL1 (bottom layer 1 of individual column footing) is designated as C1.1, which identifies storage area 1 assigned to the rebar for column C1 (Fig. 7). The bundling code for BL1 is F.C1.1.1.0 where F., C1.1., and 1.0 stand for foundation, storage area 1 for column C1, and placement sequence number 1, respectively. The zero at the end of the code indicates that the set does not need a more detailed sequencing (i.e., sequencing for each individual bar in the set). Once the rebar list (as shown in Fig. 7) is available, a graphical representation of bundling and on-site storage of sets or individual rebar elements can be created using CAD.

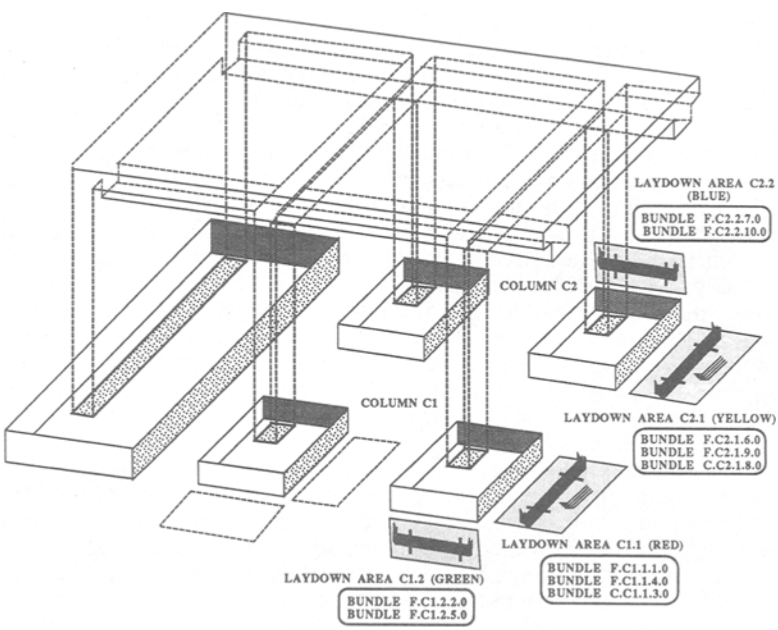

FIG. 8. Example Rebar Shakeout Plan

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Example Application

Fig. 8 presents a simple building structure with four reinforced concrete columns and one wall supporting a roof slab. Columns are supported by individual column footings, and the wall rests on a wall footing. Each column footing consists of four layers of rebar, bottom layers 1 and 2 (BL1 and BL2) for the bottom mesh, and top layers 1 and 2 (TL1 and TL2) for the top mesh. As shown in Fig. 8, bundles for each layer are separately stored in laydown areas according to the placement sequence. For example, laydown area C1.1, assigned the color code red, holds three rebar bundles for the C1 column footing, marked with red tags coded F.C1.1.1.0 (bottom mesh), F.C1.1.4.0 (top mesh), and C.C1.1.3.0 (column dowels). In this example, the bars for the bottom mesh are stacked on top of the bars belonging to the top mesh, since the rebar for the bottom mesh is needed first. Obviously, if sufficient space is available, bundles can be stored side-by-side. One other aspect to be mentioned is that the rebar is stored according to its orientation in the formwork. For example, a set is stored in parallel to its final location, which would require only a parallel translation of the bars without much time- and space-consuming handling operations. Bundles for the other columns and the wall footing are also stored in a similar manner.

The bottom line of the CRPP is to provide 3D models of the rebar placing sequence, along with a bundling scheme and on-site storage assignments, to minimize resource waste in handling bars during final assembly.

Implementation

As was demonstrated in the preceding text, the concept of this alternative approach to designing and delivering concrete reinforcement can be implemented in phases with increased sophistication.

The first, and maybe the most crucial step in implementing the concept is the recognition that the detailed preplanning of rebar-placement operation results in higher productivity, quality, and safety. Although many practitioners seem to subscribe to this notion, Oglesby et al. (1989) stated, "Today it is the unusual contractor who does formal preplanning." This statement points out that opportunities for improvements in the area of process planning are manyfold. In the same book, it is affirmed that savings due to preplanning have been reported as running up 4–15 times the cost of the planning effort. It is quite obvious that this recognition does not rely on any computer tools.

Step two, the development of a feature-based rebar-design tool, required a set of small tailored programs. For the developed system using AutoCAD, codes in AutoLISP were created and easily integrated with the main software. The codes provide a user-friendly interface and assistance in detailing. Fig. 5 shows the menu-driven implementation of the system, which allowed the rapid selection of standard rebar configurations for direct insertion into the CAD drawing of the formwork. Productivity tools are helpful in the automatic duplication of rebar, including the required spacing.

A facility that supports the manual creation of placement plans is implemented in the third step. This placement plan is created by labeling a set of rebar with a code that is able to communicate to the rebar crew the sequence for placing the bars. The presented system uses ascending numbers that represent the order of placement. Individual bars are grouped into a set of bars and labeled with a set code. Subsequently, critical drawings were automatically plotted to represent the placement sequence in a 3D format, providing a visual description of the rebar placement. These plots communicate the placement plan in a form that can be easily understood by the rebar crew.

Included in this step is the identification of possible lay-down areas for the rebar. The characterization of these areas will provide information for unloading the rebar on-site as well as input to the intelligent planner. Again, a menu-driven approach provides the necessary speed to accomplish this task efficiently.

The feature-based description of the concrete reinforcement in CAD facilitates the implementation of step 4, which is the automatic creation of a bar list. For example, through the integration of the CAD with the standard rebar data base, weights of individual bars or set of bars are easily computed.

As mentioned earlier, the creation of the intelligent process planner, listed as step 5, is not a requirement for taking advantage of the proposed alternative rebar placement-planning concept, since the plans can be obtained using the manual approach. The presented models and hierarchies for structuring the concrete reinforcement of the building, as well as the rebar assembly, supply the needed framework for the required knowledge bases. The framing of production rules can be conveniently handled by many of today's specialized software packages, such as LEVEL5 OBJECT, which was used for the system presented in this paper.

Summary and Conclusions

The total integration of detail design, fabrication, shipment, and control of placement is the key to the efficient assembly of rebar. To achieve the highest possible placement productivity, it is desirable to have the rebar delivered in the same sequence that the bars are going to be placed. A process-driven delivery concept, however, requires that a detailed process plan exists on a macro as well as a micro level. Thus, a system that interfaces detail design, delivery, and placement control could provide an efficient and cost-effective method of installation, reducing waste (e.g., time) and redundancy in the planning effort. This paper discusses the development and implementation of an alternative design and delivery model. Using a feature-oriented rebar-detailing approach, built within a common CAD software environment, an integrated placement-planning model has been implemented. The computerized version of the model is able to automatically generate, store, and communicate valuable information for shipping, storing, and assembly of rebar, and is poised to increase the productivity, quality, and safety of constructing concrete reinforcement.

Acknowledgments

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APPENDIX I. TYPICAL BAR LIST

Item	Grade	No. Pieces	Size	Length	Mark	Type	A	B	C	D	E	F	G
1	LIGHT BENDING												
2	60	22	3	8-4	3T6	T2	4	2-1	1-9	2-1	1-9		4
3	60	22	3	7-8	3T9	T2	4	1-11	1-7	1-11	1-7		4
4	60	22	3	6-3	3BT1	T2	4	1-4 3/4	1-4 3/4	1-4 3/4	1-4 3/4		4
5	60	26	3	6-3	3BT3	T2	4	1-0 3/4	1-8 3/4	1-0 3/4	1-8 3/4		4
6	60	44	3	3-4	3T10	S10		1-3 1/2	9	1-3 1/2			
7	60	22	3	2-10	3T23	T5	5	2-1	4				
8	60	52	3	2-10	3BT4	S10		1 0 1/4	9 1/4	1-0 1/4			
9	60	22	3	2-8	3T8	T5	5	1-11	4				
10	60	22	3	2-6	3T20	T5	5	1-9	4				

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