Algorithms for Reducing the Waste Rate of Reinforcement Bars

Sun-Kuk Kim*1, Won-Kee Hong2 and Jin-Kyu Joo3

1 Associate Professor, College of Architectural and Civil Engineering, Kyung Hee University, Korea
2 Assistant Professor, College of Architectural and Civil Engineering, Kyung Hee University, Korea
3 Project Manager, Shindongah E&C Co. Ltd., Korea

Abstract
Loss of rebars can be minimized with minimum use of discrete bars in market length. In order to achieve this goal, the accurate and detailed information of rebars is extracted, followed by both rapid and efficient bar combination. No paper has dealt directly with the reduction of rebar waste rates, although many researches have proposed indirect approaches to enhance productivity, constructability, safety and quality in the process of concrete reinforcement work. This paper, therefore, was prepared with the aim of developing algorithms to supply rebars required to minimize material waste during cutting and bending of discrete bars in rebar shops. At the same time, this study presented an automatic rebar detailing concept, a logical process of rebar combination with pertinent algorithms and binary search algorithm for bar data to implement the proposed topic. The effectiveness of the suggested algorithms was validated by case studies.

Keywords: rebar work; optimization; algorithm; waste rate; combination

Introduction
Countries with highly capital-intensive construction use the computerized numerically controlled (CNC) machine. The machine automatically produces shaped rebars of up to 16 mm in diameter supplied in coils which is described as machine type A by Navon, Rubinovitz and Coffler (1996). In this case, the manufacturing process of rebars produces few scraps with almost zero percent loss of raw materials. However, the generation of waste is inevitable in countries which do not supply rebars in coils and even in capital-intensive countries which can not supply rebars of larger than 16 mm diameter coils.

The straight bars of market lengths, normally 8.0, 8.5, 9.0, 9.5, .., are produced in Korea, since the raw materials for rebars are not supplied in coils. The market length production generates relatively many scraps after rebars are cutoff in required lengths.

The waste rate of scraps increases when raw materials are ordered without proper bar cutoff plans based on the structural review of drawings. The loss rate of scraps can be even higher as the diameter of rebars increases (Kim 2002). The loss of materials can be reduced when the most desired length of bars are ordered based on the sufficient review of drawings and bar schedules. Extra savings of rebars are possible when the special length of a certain amount of tonnage is ordered to steel mill.

The manual bar combination of either market length or special length to minimize the loss of materials is not an easy task since rebars of different diameters, lengths, and locations are found in various locations in drawings. In particular, in the rebar shop, the simultaneous optimum combination of the multi-projects to minimize the loss rate of material is an even more difficult problem. The optimization algorithm using computers is one of the most effective ways to solve those problems.

Previous research has shown the benefits of computer applications to improve productivity, constructability, safety and quality in the process of concrete reinforcement work. Bernold and Salim (1993) presented placement-oriented design and delivery of reinforcement based on both computer integration and feature-based design concepts. They also proposed a concept of rebar delivery and staging based on a placement plan to improve productivity on site (Salim and Berbold 1994). Dunston and Bernold (1994) produced a strategy for the robotic rebar bending based on experiments and developed a control model for accurate rebar bending based on computer integrated manufacturing (CIM) concepts (Dunston and Bernold 2000). Navon et al. (1995, 1996) described the benefits of computer-aided design and computer-aided manufacturing (CAD/CAM) systems for concrete reinforcement and developed a model for rebar constructability diagnosis and correction in an object-oriented programming environment (Navon et al. 2000).

However, the direct approach to the optimization algorithm to reduce the loss rate of rebars was not found among these papers. The work carried out by Navon et al. (1995) was one of the few studies which addressed the optimization algorithm for reducing the loss rate of rebars in a computerized way.

*Contact Author: Sun Kuk Kim, Associate Professor, College of Architectural and Civil Engineering, Kyung Hee University, 1 Seochon-ri, Kiheung, Yongin, Kyonggi-do, 449-701, Korea
Tel: 82-31-201-2922 Fax: 82-31-203-0089
E-mail: kimsuk@khu.ac.kr

(Received October 24, 2003 ; accepted April 6, 2004 )
steel rebars. However, Navon did not present the detailed algorithm even though an optimization module based on linear integer programming (LP) solver-LINDO was mentioned.

This paper, therefore, was prepared with the aim of developing algorithms to supply rebars required to minimize material waste during cutting and bending of discrete (single) bars in rebar shops.

Reasons for Loss of Rebars
The waste rate can be estimated as high as 3 to 5% in the bidding stage in countries where rebars are not supplied in coils. This rate can be even higher than 10% as the diameter of rebars increases. Kim (1987) showed that the loss rate from plant projects is higher than that of building construction in which rebars of typical length and diameter are repeated in drawings. Major causes influencing the waste rate of rebars were identified from several management processes of rebar work as follows.

(1) The highest rate of waste is observed when the purchase order with redundancy is made to steel mill without accurate understanding of manufacturing information, such as the structural drawings and bar schedules. The waste of materials rapidly increases when the proper attention is not paid to the surplus order of raw materials during the construction stage. Therefore, significant waste can be avoided if the required quantity of rebars is precisely analyzed and reflected in the mill order.

(2) Materials are also wasted when surplus rebars with length of 2-3m are not reused after cutoffs. Better economy is achieved using rebars with margins of shorter than 1m without cutoff since the cost of labor related to cutting less than 1m is more expensive. The rebars of extra length, with either straight or L shape, found from slabs and beams not only increase waste rate of materials but also add additional weight to the structure. Waste of material as high as 1% can be saved when proper bars in market length are selected for combination in order not to generate scraps of about 1m based on the structural review of drawings (Kim, 1987).

(3) It is also shown that approximately a 1% waste rate occurs when cutting planning without consideration of bending margins is carried out.

(4) One of the frequent causes of waste is the failure of inventory management of rebars cut and bent. This type of waste is observed in urgent and large-scale construction projects.

(5) It is sometimes found from construction practice that the length and location of bar splices as well as developments are not observed in compliance with codes to compensate for the loss of materials, since strict application of codes can create significant loss of materials. In these cases, therefore, the quality of rebar works is not satisfactorily controlled.

(6) Inappropriate management of rebar shops and layout of cutting and bending machines is another source of waste of materials.

The quality of labor provided by the subcontractor can significantly influence waste rate as well as rebar works. Site investigation (Kim, 1987) shows that waste of rebars decreases if optimum rebar combination and systematic inventory management are properly carried out from ordering phase to manufacturing phase. The optimum combination of rebars, calculated by computer, provides very useful information for the manufacturing of rebars as well as systematic inventory management that reduces waste rate.

Automatic Rebar Detailing Concept
The rebar combination process begins with the preparation of Rebar Data Files (RDF) based on the structural calculation. Structural design data, however, provides basic information related to arrangement of rebars. Detailed rebar information including development and splice length, concrete cover and interference of rebars is not expressed explicitly in structural drawings. Therefore, the automatic preparation of RDF from the information of structural design requires a module that provides rebar detail. Fig 1 graphically demonstrates the conceptual construction of RDF.

![Fig.1. Automatic Rebar Detailing Concept](image)

After all structural design data of structural members including number of bars, diameters, geometric size of each member, etc. are extracted from the structural design data file (SDDF), splice and development length, concrete cover related to each structural member are, then, obtained from the structural member specification data file (MSDF). As a next step, rebar manufacturing detail is prepared according to Automatic Rebar Detailing Algorithms (ARDA).

The ARDA consist of two tasks. The first task is to automatically generate rebar details of all structural members, and the second task is to estimate precise cutting lengths and quantities of rebars based on the details obtained in the first task. Each structural member needs several ARDA, depending on the arrangement condition of structural members. For example, many algorithms of beams are required for the estimation of precise cutting length and quantity of rebars, depending on bar types (bent bar, straight bar) and number of spans (single span, and multiple). Kim and Kim (1994) presented an automatic rebar detailing concept, and Kim (2002) proposed various detailing algorithms for all structural members.
An Overview of Rebar Optimization

The algorithm to reduce waste of rebars boils down to the question of how efficiently scraps generated during rebar work designated as structural drawings can be minimized. For the multiple rebars as shown in Fig. 2, the following steps are proposed for the algorithm in which \( l_i = \) combined length of rebars, \( L_i = \) length of rebars to be ordered, \( n_i = \) rebars extracted from drawings, \( i, j = \) index, \( n = \) number of \( l_i \) or \( L_i \), and \( \varepsilon = \) waste rate of combined bars.

\[ l_i: \text{bar 'a'} \quad l_i: \text{bar 'b'} \quad l_i: \text{bar 'c'} \quad n_i: 685 \text{ nos} \]

Fig. 2. Example of rebar combination

1. Find \( l_i \) where \( 0 \leq n_i (L_i - l_i)/L_i \leq \varepsilon \) \( (1) \)

2. Let \( \text{sum} = \sum_{i=1}^{m} (l_i \times n_i) \) \( (2) \)

   The sum is to be multiplied by the unit weight of each size of bars. If \( \text{sum} \approx \text{tons} \) where \( \text{tons} \) is the minimum quantity for order, then \( l_i (i=1, 2, ..., m) \) can be selected for order and it is recorded into the resource field of bar.

3. Decrease the length gradually according to the given range.

4. Repeat the process 1 and 2 until \( L_i < \text{Min (bar)} \).

Rebar Combination Process and Algorithms

Even though the proposed algorithm looks simple, it is difficult to find numerous combinations of rebars that satisfy given conditions including waste rate of material, length and quantity for purchase order as well as construction schedule. Computers can replace time-consuming manual efforts, resulting in significant savings of materials, managing cost and labor. Material waste can be minimized if the rebar combinations are obtained with not only market length but also special lengths with minimum quantity for order supplied by steel mills.

The standard lengths of rebars that can be purchased in Korean markets are 7m, 8m and 9m. Besides, it is also required by Korean Standards that 6m, 6.5m, 7.5m, 10m, 11m and 12m be provided for the construction sites. If rebars are supplied by special order, waste can be avoided further. For instance, if rebars of 320 tons with both 8.7m length and 28mm diameter are delivered to sites by special order where the same quantity of 8.7m rebars are required by structural design, the waste rate is zero. This waste rate increases up to 3.3% with a scrap bar of 30 cm when 9m rebars are supplied by the normal order. Construction costs increase rapidly when multiple projects are carried out in rebar shops with poor management systems during the ordering stage.

The special order is initially considered for the bar combination process based on reading RDF prepared by ARDA. At the same time, optimal conditions including waste rate \( \varepsilon \), quantity \( q \) and length \( l \) are read to minimize rebar waste for special orders as shown in Fig. 3. Rebars of lengths 7m, 8m and 9m, which can be easily purchased from the market by a normal order (Normal order 1), are combined to match the rest of the rebars. The final combination of rebars with the market length of 6.0m, 6.5m, 7.5m, 10.0m, 11.0m and 12.0m (Normal order 2) is performed to produce rebars whose combinations were not found. The following are the explanations of Fig. 3.

Fig. 3. An overview of rebar combination process

1. Rebar arrays are prepared by sorting out rebars of the same diameter based on readings of RDF prepared by ARDA. The arrays include length, number of identical bars and bar mark that retains the information of a bar type, diameter, spacing, and serial number. The RDF structure is very similar to the one proposed by Navon, Rubinovitz, and Coffler (1995).

2. The algorithm searches and combines rebars satisfying all the given conditions such as waste rate and quantity (for example, \( \varepsilon \leq 1\% \), and \( q_i \geq 300\text{tons} \), respectively) for rebar length specified by \( 6m \leq S_i \leq 12m \) (0.1m interval). First consideration is given to the single bars for search since combinations for single bars are not necessary. The search is extended to combinations that satisfy the given conditions with two bars. The search and combination are repeated with up to four bars.

3. The combination with more than four bars is not attempted to avoid inefficient computing time since effective inventory management of rebar shops is difficult. It was observed from a sample project that searching short rebars to be combined with primary rebars of longer lengths minimizes computing time when more than two rebars are combined. The binary search algorithm, shown in Fig. 4, is adapted among various searching methods to minimize time in finding rebars to be combined based on given conditions from hundreds of rebars sorted with respect to length. This binary search algorithm was proved by Horowitz and Sahni (1983).
The given conditions of ε (ex. ε ≤ 3%) and Lm ≤ L ≤ 12m (for L = 7, 8, 9m) are, then, implemented to search and combine rebars left over from Routine 1 (Normal order 1).

(2) Best-fit algorithm: This algorithm tries all possible combinations of every rebar stored in RDF; and a rebar combination that yields the least waste rate is selected. From the above example, the combination of a 7m rebar and a 3m rebar out of a possible six rebar combinations gives the least waste rate of zero while a waste rate of 2% calculated from 7m+2.8m rebar combination was obtained by the First-fit algorithm. This algorithm will not lose the chance to minimize waste rate, despite unavoidable computational time.

(3) Modified-first-fit algorithm: This algorithm applies differentiated waste rate. Main rebars are combined within a specified waste rate (for example, waste rate of 1%) and a relieved condition waste rate, such as 3%, is applied to the rest of the rebars. However, the overall waste rate must not be beyond the target waste rate, such as 2%. It was shown from the algorithm test that quantities combined based on the relieved waste rate do not exceed 10% of total rebars under combination. This algorithm is considered to be the best algorithm empirically in maximizing combination efficiency and applicability while minimizing computing time.

Algorithms for Mathematical Programming

It was shown that several algorithms must be combined to solve optimization problems minimizing rebar waste rates. This study presented solutions to the following questions. (1) How can one prepare rebar-detailing algorithms from the information of structural design? (2) How can one find a logical process for rebar combination? (3) What type of conditions must be imposed to combine rebars for each process (first or best-fit algorithm)? (4) How can one rapidly search bar data to be used for rebar combination (binary search algorithm)?

Besides, the problem as to how one can quickly calculate rebar quantity satisfying given requirements remains unanswered. Numerous calculations of rebar quantity are required to generate a candidate solution and numerous candidate solutions must be obtained to find an optimum solution. Algorithms from mathematical programming are necessary to expedite such complicated calculations. Solving of the optimization of rebar work is described by linear programming. Algorithms based on Equations (1) and (2) can be suggested using data read from RDF as a form of array.

\[
\begin{align*}
\text{procedure } \text{BINARITY}_{\text{SEARCH}}(F, n, i, K) \\
// Search a RDF(F) sequentially ordered in length with bar records \ R_1, \ldots, \ R_n \text{ and the keys } K_1 \leq K_2 \leq \ldots \leq K_n \text{ for a record } R_i \text{ such that } K_i = K; \ i = 0 \text{ if there is no such record else } K_i = K. \text{ Throughout the algorithm, } i \text{ is the smallest index such that } K_i \leq K \text{ and } u \text{ the largest index such that } K_u \text{ may be } K// \\
i \leftarrow 1; \ u \leftarrow n \\
\text{while } i \leq u \text{ do} \\
m \leftarrow \lfloor (i + u) / 2 \rfloor \\
// \text{compute index of middle bar record}// \\
\text{case} \\
\text{: } K > K_m; \ l \leftarrow m + 1 \\
// \text{look in upper half}// \\
\text{get special order} \\
// \text{test optimization for special order}// \\
: K = K_m; \ i \leftarrow m; \ \text{return} \\
: K > K_m; \ u \leftarrow m - 1 \\
// \text{look in lower half}// \\
\text{get special order} \\
// \text{test optimization for special order}// \\
\text{end} \\
\text{end} \\
i \leftarrow 0 \quad // \text{no record with key } K// \\
\text{end} \text{ BINARITY}_{\text{SEARCH}}
\end{align*}
\]

Fig. 4. Binary search algorithm for rebar combination

\[
\begin{align*}
\text{Decision variables} \\
P &= \text{total sum of combined rebars for all structural members} \\
Q &= \text{total sum of rebars to be ordered for all structural members} \\
p_1, \ldots, p_n &= \text{sum of rebars combined in a certain length} \\
q_1, \ldots, q_n &= \text{sum of rebars to be ordered in a certain length}
\end{align*}
\]
Objective Function

Minimize \( \frac{Q - P}{P} \) or \( \frac{P - Q}{P} \)

Subject to

\( q_1, \ldots, q_n \geq \text{tons} \)

\( \frac{q - P}{P} \leq \varepsilon \) or \( \frac{Q - P}{P} \leq \varepsilon \)

Where the weight (tons) is the minimum quantity of a purchase order, and \( \varepsilon \) represents the waste rate defined by users. Decision variables, \( P, P, Q, q \), of Equations (3) and (4) are calculated by Equations (7), (8), (9) and (10).

\[ P = \sum_{i=1}^{n} w_i P_i \]

Where \( w_i \) is the unit weight of the rebar. One rebar element, \( P_i \), out of all rebars combined within a certain length, \( \{P_1, \ldots, P_n\} \), is expressed as Equation (8).

\[ P_i = \sum_{j=1}^{n} a_j x_j = a_1 x_1 + \cdots + a_n x_n \]

Where \( a_1 \) is the number of rebars combined within a certain length and \( x_1 \) is the actual length of combined rebars. The quantity of rebars to be ordered in a certain length is given in Equation (9).

\[ Q = \sum_{i=1}^{n} q_i \]

One rebar element, \( q_i \), out of all rebars to be ordered in a certain length, \( \{q_1, \ldots, q_n\} \), is obtained from Equation (10).

\[ q_i = y \sum_{j=1}^{n} a_j = y (a_1 + \cdots + a_n) \]

Where \( y \) is the market length of rebars to be ordered.

Test Results of Proposed Algorithms

The algorithm presented in this study was programmed with Visual C++ 4.0. Both the accuracy and applicability to sites of the theory was validated by a case study of high-rise residential buildings described as follows.

- Location: Yongin-si, Kyonggi-do, Korea
- Total floor area: 92,435 m\(^2\) (20 stories x 5 buildings)
- Structure: Bearing wall system
- Duration of main structural work: June, 2000 - December, 2000 (6 months except foundation work)

Five buildings managed by the same schedule of reinforcement work were considered for system tests in this study even if the complex consisted of 20 buildings. Tables 1 and 2 are the results of the combination for the 16mm rebar most frequently used in the project. Every rebar was assumed to be systematically managed during the 6 month construction period of the main structural framework. The combination was performed for structural members of all floors (1st-20th floor) of 5 buildings except the foundation. Table 1 is a combination list for the special order (combination number S1) of 10.6m long rebar. Rebars are combined with the maximum material loss (waste rate) of 1.0% and minimum quantity of 300 tons.

| No | D | L | Dg No | B.M. | Nos | Other Sources |
|----|---|---|-------|------|-----|--------------|
| S1-1 | T16 | 10.600 | S0101 | 0020 | 925 |
| S1-2 | T16 | 10.600 | S0102 | 0049 | 1,650 |
| S1-10 | H16 | 10.500 | S0203 | 0602 | 986 |
| S1-11 | B16 | 8.150 | S0103 | 0085 | 660 |
| S1-12 | B16 | 2.420 | S0102 | 0054 | 660 |
| S1-11 | B16 | 8.100 | S0109 | 0262 | 418 |
| S1-12 | B16 | 2.480 | S0105 | 0155 | 418 |
| S1-11 | B16 | 8.100 | S0109 | 0262 | 418 |
| S1-11 | B16 | 8.100 | S0109 | 0262 | 418 |

Test Results of Proposed Algorithms

The modified-first-fit algorithm was used to economically combine rebars designated as in the first column of Table 1. These rebars meet specified combining conditions. Single rebar lists without the need of bar combination are shown by S1-1 through S1-10. S1-11 is the list of special orders for combinations with two rebars. For example, the waste rate is zero since the rebars represented by S1-1 and S1-2 is 10.6m. S1-10 generates a waste rate of 0.94 % and is included in the list. S1-11, which combines Bars 0083 and 0054, satisfied the condition of special order with waste rate of 0.28 %. The modified-first-fit algorithm, which selects long rebars, is followed by the combination of short rebars to
reduce computing time. All Bars 0085 are used for S-11 combination, whereas only 660 bars from bars 0054 (the total of 1645 bars) are used for the combination of S1-11 (Table 3). The rest of bars 0054 are used to combine S1-24, S3-5, N1-18, N15-3 as shown in Table 1.

Finally, Table 1, containing results of the combination of 23,945 rebars of length 10.6m, compares the order weight of 395.955 tons with the net weight of 393.702 tons, demonstrating a waste rate of 0.469%. The real diameter of the nominal 16mm diameter rebar is 15.9mm while the unit weight is 1.56kg/m in KS (Korean Standard). Rebar notations are defined by T16, H16 and B16 instead of Y16 to clearly indicate the diameters and locations of rebars. T, B, H, V and M represent top, bottom, horizontal, vertical and middle bar, respectively.

Table 2 shows the combination list for normal orders (combination number N1) of 9.0m long rebars. For this combination, the maximum loss is 1% and there is no limit to the minimum quantity for order. Rebars of 7, 8, and 9m are combined first according to the algorithm employed in this study and the combination based on rebars of 6.0m, 6.5m, 7.5m, 10.0m, 11.0m and 12.0m is followed. However, the execution of combinations of 11m and 12m rebars is delayed till the order from site due to the traffic condition.

Table 3 represents rebar sources of combination managing all combined rebars by bar number. It provides systematic tools for inventory management of rebar cut off, enabling a bar bending process quickly and effectively. Without these lists, it is difficult to locate combined rebars for bar bending even if the rebar combinations are successfully performed. For example, since rebars 0054 are used for the combinations of S1-11, S1-24, S3-5, N1-18, N15-3, one must keep track of each combination to locate 1,645 rebars. Table 3 demonstrates results of all combined rebars, while rebars of the same diameter can be printed out if necessary. The detailed manufacturing information of Table 3 which can be checked from the rebar schedule and bar tag as shown in Fig. 5 is used to facilitate inventory management of manufactured rebars.

Table 3. Rebar Source of Combination

| Conditions | $SS$ SOURCES OF COMBINATION $SS$ |
|------------|----------------------------------|
| B.M. D L Dwg. No Nos Sources | Sources |
| 0001 T13 4.850 S0101 1,482 S13-8, S15-3, N25-1 | |
| 0002 T13 8.650 S0101 1,466 S3-2 | |
| 0003 T13 9.000 S0101 1,482 N1-1 | |
| ... ... ... ... ... ... | ...
| 0054 T16 2.420 S0102 1,645 S11-1 S1-24 S3-5 N1-18 N15-3 | |
| 0055 T16 6.250 S0102 363 S5-5 S7-2 N8-2 | |
| 0056 B16 3.855 S0102 526 S3-10 N3-14 N9-2 | |
| ... ... ... ... ... ... | ...
| 0562 H16 9.000 S0202 1,362 N1-3 | |
| 0563 V16 4.200 S0202 2,465 S3-6 S4-4 N2-6 N3-5 N5-4 | |
| 0564 H13 9.000 S0202 1,230 N1-2 | |

The difference of 40mm in length between Table 3 and Fig. 5, called bending margin, resulted from the increase during bending process. In case of deformed bars, the bending margin is calculated by 2.5 times of the rebar size in diameter.

The difference of 40mm in length between Table 3 and Fig. 5, called bending margin, resulted from the increase during bending process. In case of deformed bars, the bending margin is calculated by 2.5 times of the rebar size in diameter.
quantity. The actual construction data revealed that the project used 3,007.97 tons of 16mm rebar, generating the waste rate of 3.246%. The waste rate could have been reduced down to 0.819%, saving 70,705 tons of rebar (2.427% waste rate) equivalent to 30,300 USD (about 35 million Korean won) if the algorithm proposed by this study had been implemented for the construction management of rebar work. If the construction of all 20 buildings under consideration had been carried out applying the algorithm of this paper, approximately 400 tons of steel worth 170,000 USD (199 million Korean won) could have been saved.

Conclusions
A considerable waste rate occurs if sufficient attention is not paid to the management of complex rebar work of construction projects. A great deal of rebars can be saved with increased productivity when purchase orders, manufactures and installations are carried out according to construction schedules, while both rebar details and required optimal rebar quantities are prepared based on the algorithm presented in this study.

The example run demonstrated the reduction in the waste rate by about 2.4 percentage points by implementing the algorithm of this paper. Relatively much reduction of waste is expected from plant construction involved with various types of rebars than from the construction of high rise residential and commercial buildings in which rebars of typical length and diameter are repeated throughout design.

The example study also demonstrated the combination algorithm, among all algorithms presented in this research, enhances not only computing efficiency but also the efficiency of rebar management related to construction schedules. The modified-first-fit algorithm is considered to be the best algorithm empirically in maximizing combination efficiency and applicability while minimizing computing time.

The prompt extraction of precise rebar data from structural design data was a difficult task in this study. A more efficient format, automatically using structural design data for the management of rebar work, needs to be developed in order to effectively deal with a series of works including structural design, the preparation of structural drawings and rebar details, and optimization of rebar work.

References
1) Bernold, L.E., and Salim, Md. (1993) “Placement-oriented design and delivery of concrete reinforcement.” J. Constr. Engrg. and Mgmt., ASCE, 119 (2), 323-335
2) Dunston, P.S., and Bernold, L.E. (1994) “Adaptive control for robotic rebar bending.” Microcomputers in Civ. Engrg., Oxford, England, 9, 53-60
3) Dunston, P.S., and Bernold, L.E. (2000) “Adaptive control for safe and quality rebar fabrication.” J. Constr. Engrg and Mgmt, ASCE, 126 (2), 122-129
5) Horowitz, Ellis, and Sahni, Sartaj (1983) “Fundamentals of data structures”, Computer Science Press, Inc., Maryland, 342
6) Kim, S.K. (1987), “A Report of Rebar Waste Rate Analysis of RC Structures”, Daelim Industrial Co., Ltd., Korea, 16-17
7) Kim, S.K., and Kim, C.K. (1994) “Integrated Automation of Structural Design and Rebar Work in RC Structure”, J. Structure and Construction, the Architectural Institute of Korea, 10(1), 113-122
8) Kim, S.K. (2002) “A System Development for Automatic Detail Design and Estimation of Rebar Work”, the 1st year Research Report, Gyeonggi Regional Small & Medium Business Administration, Korea, 84-90
9) Navon, R., Rubinovitz, Y., and Coffler, M. (1995) “RCCS: Rebar CAD/CAM System” Microcomputers in Civ. Engrg., Oxford, England, 10, 385-400
10) Navon, R., Rubinovitz, Y., and Coffler, M. (1996) “Fully automated rebar CAD/CAM system: economic evaluation and field implementation.” J. Constr. Engrg and Mgmt, ASCE, 122 (2), 101-108
11) Navon, R., Shapira, A., and Shechori, Y. (2000) “Automated rebar constructability diagnosis.” J. Constr. Engrg and Mgmt, ASCE, 126 (5), 389-397
12) Salim, M., and Bernold, L.E. (1994) “Effects of design-integrated process planning on productivity in rebar placement.” J. Constr. Engrg. and Mgmt., ASCE, 120 (4), 720-738