An Innovative Technology in Concrete Construction: Semi-Automated Rebar Tying

by

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Abstract

The two main purposes of this thesis are to present the design of a new prototype rebar tying tool and to characterize technological development in concrete construction.

The technologies of concrete construction have undergone gradual, evolutionary changes since concrete became a popular material for construction. Furthermore, these technological developments can be characterized as an active, industry-wide progression from fully manual operations to fully automated operations. This thesis will present a snapshot of the current state of the art in concrete technology, as well as illustrating the major steps that individual technologies have taken on their evolution to the present status.

The thesis continues with a chapter covering an analysis of the task of rebar tying, which contains examples of other unsuccessful attempts to automate the task. The functional requirements and design criteria for an improved semi-automated rebar tying machine are then presented. A new prototype rebar tying tool has been designed based on the developed requirements. The operation of the pneumatic device and its detailed design is included in Chapter 4.

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CHAPTER 1
INTRODUCTION

1.1 Overview and Purpose

One operation in the construction of reinforced concrete is the assembly of reinforcing bars. The reinforcing steel, known as rebar, is assembled by hand tying the intersections of the bars with wire. Since a majority of concrete construction is flatwork, workers are required to bend over for long periods of time while assembling the reinforcement.

The two main purposes of this thesis are to characterize technological innovation in concrete construction and to present the design of an innovative, semi-automated rebar tying machine for concrete construction. The device will enable a worker to tie rebar from a standing position, thereby eliminating the grueling aspect of the task, bending over for long periods of time. It will also allow lower skilled, lower cost labor to perform the task at higher levels of worker productivity and with improved consistency and quality of the finished product.

This chapter will first present a brief history of concrete usage, depicting the rich heritage of concrete construction worldwide. The economics of the concrete industry and of rebar tying in particular will then be discussed, followed by a look at some of the potential impacts of the innovative device presented here.

1.2 Brief History of Concrete Usage

Concrete, one of the oldest building materials in use today, was first used over two thousand years ago by the Romans in the construction of buildings, bridges, and other structures. One notable structure is the Pantheon in Rome, with its cast-in-place concrete "Great Dome," which still stands today. The Romans used cast-in-place concrete for the underwater construction of quay walls and small jetties, and used precast concrete blocks to build large jetties.[1] After the fall of the Roman Empire, concrete usage virtually disappeared until 1756, when English engineer John Smeaton used it to build Eddystone Lighthouse off the coast of Plymouth, England.

Reinforced concrete came into use in the 1800's, with patents issued to numerous inventors. Perhaps the most famous of the early inventors is the well known Joseph Monier, who received a patent in 1867 for reinforced concrete flower pots. Monier would later receive additional patents for floors, beams, pipes, bridges, and other items. Although Monier received the most recognition, he was not the first to receive a patent for reinforced concrete. Earlier patent recipients included Lambot in 1855 for a reinforced concrete boat, Francois Coignet in 1861, and Hyatt for reinforced concrete beams.[2]

In the United States, unreinforced concrete buildings began to appear as early as 1835. The William Ward House, which is believed to be the country's first cast-in-place reinforced concrete structure, was constructed shortly after. It was built in Port Chester, New York, and was completed in 1875.[3] Today, concrete, wood, and steel remain the three most commonly used materials in construction.

Concrete's popularity can be attributed to its favorable engineering and aesthetic properties. In addition to being strong and stiff, it is durable and corrosion resistant. Architecturally, it can be fashioned into an almost infinite number of shapes having numerous surface finishes.

Concrete is economical for a multitude of applications. The components, sand, gravel, and portland cement, are widely available and can usually be produced from local materials. In addition, concrete is much easier and less expensive to process than steel. With increasing emphasis being placed on the lifecycle costs of structures, it is likely that concrete, which requires little maintenance and is extremely durable,

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[1] Hans Straub, A History of Civil Engineering, (Cambridge, MA: The MIT Press. 1964), pp. 20-21.

[2] Ibid, pg. 209.

[3] Edward Cohen and Raymond C. Heun, "100 Years of Concrete Building Construction in the United States," Concrete International, March, 1979.

will grow in popularity and use for major projects.

In recent years, concrete has been showcased in the finest structures built. Concrete is the primary structural material in thirty-five percent of projects nominated for ASCE Outstanding Engineering Achievement Awards over the past three years, and is a substantial component in another thirty-five percent.

1.3 Economics of Concrete Construction

In addition to concrete's importance as a durable, economical construction material, and its rich history as an engineering and architectural building component, the concrete construction industry is important to the nation's economy. Concrete construction is roughly a 15 billion dollar per year industry,[4] or about 3.6 percent of the 414 billion dollar per year construction industry.[5] There are over 23,000 concrete construction firms in the industry, employing over 200,000 workers.[6] The health of the industry will therefore affect the health of the overall economy and the lives of many American workers. These economic realities provide some of the motivation for the development of innovative, productivity enhancing technologies in concrete construction.

Given the economic importance of concrete construction, one wonders how in 1987, concrete construction contractors spent 3.3 billion dollars on direct labor costs, but just 200 million dollars was spent on machinery and equipment.[7] It would seem that there is little investment in labor saving equipment and devices. However, the next chapter will portray the evolution of technologies for concrete construction, showing

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[4]U.S. Department of Commerce, Bureau of the Census, 1987 Census of Construction Industries, "United States Summary, Establishments With and Without Payroll," p. 7.

[5]U.S. Department of Commerce, Bureau of the Census, Current Construction Reports, "Value of New Construction Put in Place," April, 1990, p. 3.

[6]U. S. Department of Commerce, Bureau of the Census, 1987 Census of Construction Industries, "Concrete Work Special Trade Contractors, Industry 1771," p. 2.

[7]U. S. Department of Commerce, Bureau of the Census, 1987 Census of Construction Industries, "Concrete Work Special Trade Contractors, Industry 1771," p. 6-7.

that indeed the technology is developing and is being adopted by the industry, and that the industry is shifting emphasis to mechanized and automated operations.

1.4 Economics of Rebar Tying

Each year, 90 million tons of portland cement, over 5 million tons of reinforcing bars, and 530 million tons of aggregate are used in the production of 655 million tons of concrete.[8] (Aggregate weight was computed by using an estimate of the weight of fresh concrete.)[9] Means' Concrete Cost Data, 1990 lists the unit cost of placing one ton of reinforcing steel at $440.00 for lots averaging ten tons, and $325.00 for lots over fifty tons.[10] If Means is correct, then between 1.625 and 2.2 billion dollars is spent each year to place and tie rebar.

If a labor saving device, such as a semi-automated rebar tying machine, could be developed, and direct labor costs could be reduced by ten percent, the resulting yearly savings would be between 162 and 220 million dollars!

1.5 Potential Impacts of Semi-Automated Rebar Tying

1.5.1 Effect on Competitiveness of Concrete

Since the primary basis of competition in the concrete construction industry is price, any cost savings that could be achieved would improve the industry's ability to compete against substitute products. Reinforced concrete competes against steel for structural uses. There are really no other feasible materials for structures of reasonable size. The decision of whether or not to use concrete (structural, not architectural) is one of economics. The least expensive system is usually chosen. Decreased cost for concrete will therefore improve its strategic position in the overall

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[8]U. S. Department of Commerce, International Trade Administration, "Construction Review," May-June, 1990, p. 47.

[9]Portland Cement Association, Design and Control of Concrete Mixtures, Twelfth Edition, 1979.

[10]William D. Mahoney, Editor, Means Construction Cost Data, 1990, p. 63.

construction industry.

1.5.2 Effect on Workers and Worker Productivity

The design to be presented of the prototype rebar tying device allows the tying operation to be performed from a standing position. This will reduce the occurrence of repetitive stress injuries to the backs of workers. In addition, fatigue will not slow worker production near the end of a shift, when typically the effects of prolonged bending over are most pronounced, resulting in increased productivity of the tying operation.

Another impact that the device will have on workers is that it will allow lower skilled labor to perform rebar tying at the same or greater levels of productivity as skilled steel workers. In effect, some of the skill in the task is being shifted from the worker to the machine, providing greater job opportunities for lower skilled workers, and allowing higher skilled workers to do less repetitive work, and work that is ill suited to the device.

1.5.3 Economic Impacts

It is very difficult to discuss the economic impacts of productivity increases in quantitative terms. One problem is with what productivity to measure. The task of rebar tying is simply a sub-task of the reinforcement placing operation. It is desirable to improve this overall operation, not the tying task. While one can design a device to perform tying in a specified amount of time (improving tying efficiency), it is difficult if not impossible to numerically predict the effect on the overall operation without making quantitative assumptions of how the new method will interact with the overall operation. Similarly, since cost data is compiled for the placement of reinforcement, not the sub-task of rebar tying, meaningful quantitative predictions of cost savings (from enhanced productivity) cannot be made.

Qualitative estimates of cost savings from increased productivity can be made. The device will have the greatest impact on applications with horizontally placed reinforcing steel, including slabs, floors, and bridge decks, that traditionally would have required the worker to bend over to place the steel. Since about 75% of concrete work is horizontal construction, the impact of the device should be widespread.

An interesting finding is that the cost per pound to place reinforcing steel is almost identical for all applications except columns and waffle slabs, where it is about 30% more expensive.[11] It seems that the cost of placing reinforcement for a concrete structure is independent of the type of structure and almost entirely dependent on the quantity of reinforcement to be placed. Therefore, highly reinforced structures will become more economical than before, while lightly reinforced components will realize less cost savings.

The greatest cost impact is likely to be from the use of lower cost labor, made possible by the lower skill level required with the device. Quantitative predictions can be made regarding cost savings from the use of lower cost labor. A twenty city average of union pay scales showed that reinforcing ironworkers are paid $25.31 per hour, while skilled laborers received only $18.46 per hour.[12] If only half of the ironworkers were replaced with laborers, a 13.5 % savings would be realized, resulting in an industry wide savings of between 220 and 300 million dollars.

1.6 Automated Rebar Tying for Fully Automated Rebar Fabrication

In Chapter 2, technological innovation in concrete construction will be characterized as an active, industry-wide progression from fully manual operations to fully automated operations. The automation of rebar tying will represent a significant step toward that goal. It is feasible that in a few years, fully automated precast plants may be in operation. Automated site operations may become widespread. For total process automation to be possible, automated rebar tying or some other automated joining method must be developed.

The proposed device is a semi-automated, manually operated machine, but it is by no means limited to that mode of operation. It is expected that subsequent versions of the device will be adapted for use in a totally automated rebar fabrication machine, with integrated rebar cutting, bending, and tying. Currently, automated systems for

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[11] William D. Mahoney, Editor. Means Concrete Cost Data, 1990.

[12] WIlliam G. Krizan and Steven W. Setzer, "Wage Hikes Fall Below Inflation," ENR Third Quarterly Cost Report, September 27, 1990.

bending and cutting rebar are being developed. Once the mechanization of the rebar tying task is completed, it can be integrated with the other processes to create a fully automated, computer controlled system for fabricating rebar.

CHAPTER 2
TECHNOLOGICAL DEVELOPMENTS IN CONCRETE CONSTRUCTION

2.1 Characterization of Technological Developments in Concrete Construction

Technologies are often classified as product technologies and process technologies. When concrete technologies are examined using such a model, distinct characterizations of technological development in each category can be made. Both types of technology have developed in a similar, evolutionary manner. Continual, incremental improvements have occurred to both product and process technologies. However, the characterizations of the types of improvements which have been made to each class of technology are different.

The development of product technology can be characterized as an expansive development. In other words, the types and characteristics of concrete products have been continually developing, creating more and different varieties of concrete with increased capabilities. The result is the utilization of concrete products for an expanded number of construction applications. New product technologies in concrete construction include such things as new types of portland cement, new additives and admixtures, fiber reinforcement, precast concrete, prestressed concrete, etc.

Process technologies in concrete construction show a slightly different trend. A model for the development of process technologies which seems to apply nicely to concrete construction is the model for process automation. The successful automation of a process is inherently easier if the process is already highly mechanized. In this case, the problem of automating the task simplifies to a problem of developing system logic and controls. Typically, the development of process automation is accomplished by taking a manual operation, mechanizing it, improving the mechanization, and finally taking the operation out of the hands of the machine operator through total automation.

The process technologies of concrete construction can be shown to conform to this model. They have undergone gradual, evolutionary changes since concrete became a popular material for construction. Furthermore, the developments can be characterized as an active, industry-wide progression from fully manual operations to fully automated operations. Although some processes are still performed manually, most have undergone some degree of mechanization, and many have progressed to the automation stage.

Another trend in process technologies, which will be referred to throughout this chapter, is the elimination of some of the processes in the concrete construction operation. The use of mechanized and automated methods sometimes makes other steps in the process unnecessary. Examples of construction methods that eliminate steps in the process include use of prefabricated welded reinforcing mats, slipforming, and tilt-up construction.

This chapter will present a snapshot of the current state of the art in concrete technology. In addition, the major steps that each individual technology has taken on its evolution to the present status will be illustrated, emphasizing the different characterizations of development in each class of technology. Although developments in product and process technologies necessarily impact each other, they will be discussed separately below.

2.2 Innovations in Concrete Product Technology

2.2.1 Concrete Design

Structural design technology has advanced considerably. One of the earliest designs for a reinforced concrete beam was by Hyatt, who through intuition or an "educated" guess, correctly placed the reinforcing steel in the tension side of the beam.[13] Today, we have a vast amount of knowledge of the mechanics of reinforced concrete, resulting from years of research, and can produce designs to resist gravity, wind, and seismic loads.

[13] Hans Straub, A History of Civil Engineering, The MIT Press, Cambridge, MA, 1964, pg. 209.

Advances in concrete design have also produced entirely new configurations of concrete and reinforcement. As early as 1923, a water tank was "prestressed" by using adjustable bands. Two years later, in 1925, the first post-tensioning system for embedded reinforcing bars received a patent. However, it wasn't until 1938 that the first "real" prestressed structure, a shell dome, was built. Prestressed concrete was first used in bridge construction in the United States in 1949, for the Walnut Lane Bridge. In the following year, the first prestressed pavement was constructed.[14]

Widely used today, prestressed concrete is typically reinforced with very high strength stranded wire (about four times as strong as the steel in conventionally reinforced concrete), although high strength prestressing rods are sometimes used. An innovative application of prestressing technology that is gaining popularity is the external prestressing of concrete members that are in need of repair or are found to be inadequate.

The development of prestressed concrete has expanded the use of concrete. More applications are possible since prestressed concrete allows the design of lighter members and it allows the designer to control deflections.

2.2.2 Concrete Mix Design

"The goal of practical mix design is to develop a concrete that can be produced, transported, and placed efficiently and consistently to obtain the specified in-situ quality."[15] As production, transportation, placement, and finishing technologies have evolved, new mix designs have been developed to meet the changing requirements.

One of the most exciting areas of concrete mix design that continues to develop is the design of high strength mixes. High strength concrete mixes have been produced to enable the construction of concrete structures with very highly stressed members that would be impossible with lower strength concrete.

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[14] "Memorable Miscellany," Concrete International, October, 1979.

[15] Hanne Ronneberg and Malvin Sandvik, "High Strength Concrete for North Sea Platforms," Concrete International, January, 1990.

It is interesting how the notion of "high strength" has evolved coincident with the development of higher and higher strength mixes. In 1958, high strength concrete (6000 psi) was used to reduce the required size of columns in a Dallas apartment building. In 1973, a strength of 7500 psi was used for One Thousand Lake Shore Plaza in Chicago. The following year, 12000 psi high strength concrete was developed.[16] Currently, concrete strengths of greater than 9000 psi are considered high strength and state-of-the-art high strength mixes achieve strengths of up to 17000 psi.

2.2.3 Portland Cement

Until 1824, only natural cements extracted from pozzuolanic soils (found in regions rich in volcanic deposits) were used to make concrete. In October of that year, Joseph Aspdin applied for a patent for artificial cement. He named the cement "Portland Cement," because it resembled a commonly used building material, Portland Stone.[17]

Numerous varieties of portland cement have been developed in response to widely differing special applications and design requirements. A fairly extensive list has been compiled of different varieties of portland cement and their particular applications. It is presented in Appendix 1, but will not be discussed in detail here.

2.2.4 Aggregate

Seventy-five percent of the volume of reinforced concrete is aggregate. Originally, aggregates were quarried from natural sand and gravel deposits. However, the increasing difficulty of finding readily accessible deposits led to the development and use of crushed stone aggregates. Today, about 50% of the aggregate used in concrete is crushed stone.

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[16] Jaime Moreno, "225 W. Wacker Drive," Concrete International, January, 1990.

[17] Hans Straub, A History of Civil Engineering, The MIT Press, Cambridge, MA, 1964, pg 207.

Although standard weight aggregates are used almost exclusively, lightweight aggregates have been developed for special applications of lightweight structural concrete. Slag was first studied for use in concrete in 1917, and today expanded slag is one form of lightweight aggregate.[18] In 1918, expanded shale aggregate, the first synthetic lightweight aggregate, was patented by Stephen Hayde.[19] Other synthetic lightweight aggregates include expanded clay and expanded slate.[20] Very lightweight aggregates have been developed for use in lightweight, low strength, insulating concrete. Such aggregates include perlite, vermiculite, and expanded polystyrene beads.[21]

Similarly, heavyweight aggregates have been developed for special applications of heavyweight concrete including radiation shielding and counterweights for movable bridges. High density aggregates include barite, ferrophosphorus, goethite, hematite, limonite, magnetite, lead, and steel shot.[22]

2.2.5 Additives and Admixtures

Additives encompasses a wide range of materials which have been developed to enhance the properties and performance of concrete. Admixture research began in the twenties. In the mid-thirties, it was found that air-entrainment increased the durability of concrete,[23] and by the forties, vinsol resin was being used for air-entrainment. As early as 1936, pozzolan was used in concrete for the Bonneville

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[18] "Memorable Miscellany," Concrete International, October, 1979.

[19] Edward Cohen and Raymond C. Heun. "100 Years of Concrete Building Construction in the United States," Concrete International, March, 1979.

[20] Joseph J. Waddell, Editor, Concrete Construction Handbook, McGraw-Hill Book Company, New York, 1968.

[21] Design and Control of Concrete Mixtures, Twelfth Edition, Portland Cement Association, Skokie, Illinois, 1979, pg. 128.

[22] Ibid, pg. 132.

[23] Edward Cohen and Raymond C. Heun. "100 Years of Concrete Building Construction in the United States," Concrete International, March, 1979.

Dam.[24] In the mid-fifties, set-retarding admixtures were developed. By 1971, melamime resin was being studied as a water-reducing, high strength additive. In the early seventies, polymer concretes were developed.[25]

Today, admixtures provide the construction professional increased flexibility of construction practices and the mix designer the ability to create higher quality mixes and special purpose mixes. Commonly used admixtures and their primary purposes are presented in Appendix 2.

2.2.6 Reinforcement

In addition to the development of prestressed concrete, as mentioned above, other developments in reinforcing technology have been made. Prior to 1926, reinforcing steel was highly non-uniform. In 1926, standards for reinforcing steel were accepted. The standards allowed the use of one grade of steel rather than three, and of eleven sizes of rebar rather than twenty-six.[26] In 1940, Carl Menzel patented a prototype of the modern, deformed reinforcing bars used today.[27] Currently, eleven standard bar sizes are still accepted, and the overwhelming majority of rebar is grade 60 steel, although some grade 75 steel may also be used.

Other materials have been developed to reinforce concrete. These include smooth steel bars, various types of fibers (discussed in detail below), and bamboo in some undeveloped countries. Epoxy coatings have been developed for rebar in applications where corrosion resistance is a concern, and is standard on many bridges. Composite prestressing tendons made of glass fibers and polyester resin have been developed and have been used in highly corrosive environments for some bridge components and for precast elements of a brine tank.[28]

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24 "Memorable Miscellany," Concrete International, October, 1979.

25 Ibid.

26 "Memorable Miscellany," Concrete International, October, 1979.

27 Edward Cohen and Raymond C. Heun. "100 Years of Concrete Building Construction in the United States," Concrete International, March, 1979.

28 Reinhard Wolff and Hans-Joachim Miesseler, "New Materials for Prestressing and Monitoring Heavy Structures," Concrete International, September, 1989, pp. 86-89.

Secondary reinforcement to control the spread of cracks traditionally consisted of welded wire mesh or deformed welded wire mesh. Fiber reinforcement is now often used in its place. Research on concrete reinforced with nylon fibers began in the late sixties. Glass fibers were reported to be successfully used in concrete by 1969, the same year that a patent was issued for a steel fiber reinforcing method. By 1971, the first fiber reinforced pavement was constructed in Ohio.[29] Other fibrous materials which have been proposed include wood and polypropylene.

2.2.7 Precast Concrete

While precast concrete can be thought of as a process which speeds concrete construction through utilization of off-site production, it will be considered as a concrete product in this thesis. Precast concrete, as mentioned in Chapter 1, was used over 2000 years ago by the Romans. Thomas Edison is responsible for one of the earliest modem day uses of precast concrete in the United States in his effort to produce affordable low-income homes. The project consisted of the construction of eleven two-story houses, called the Edison houses, in Union, New Jersey, in 1902. This was the first use of concrete for industrialized housing.[30]

By 1917, precast concrete construction was used for a wide variety of structures.[31] The development of the technology to date has resulted in the widespread availability of numerous standard shapes for applications as varied as bridge girders, floor slabs, pipes, culverts, and manholes.

Developments in concrete product technology has expanded the use and applicability of concrete in construction. New process technology, however, has made widespread concrete use possible. If mechanized and automated technologies had not been developed, concrete use would have been limited by the high cost of manual methods.

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[29] "Memorable Miscellany," Concrete International, October, 1979.

[30] Edward Cohen and Raymond C. Heun. "100 Years of Concrete Building Construction in the United States," Concrete International, March, 1979.

[31] "Memorable Miscellany," Concrete International, October, 1979.

2.3 Innovations in Concrete Process Technology

2.3.1 Structural Design and Detailing

The process of concrete construction can be said to begin with the design engineer, for without a good design and construction drawings to communicate it, the remaining processes would proceed without direction. The design process has progressed a great deal since Hyatt received his first patent many years ago. In fact, the design process has been completely rationalized. Currently the limit states design methodology, which was first proposed in the fifties and was fully accepted in the 1971 code,[32] is the established benchmark for design.

Reinforced concrete design has developed into a highly mechanized and automated process. Initially, all design calculations were done by hand. Now, computer aided detailing and computer programs for analysis and design, both introduced in the early sixties,[33] are in widespread use and have radically changed the way concrete is designed and construction details are drawn. Today, libraries of computer software programs are available for concrete design. In addition to the many commercial vendors of concrete design software, the American Concrete Institute and the Concrete Reinforcing Steel Institute each offer their own sanctioned software programs.

2.3.2 Concrete Mix Design

Mix design has developed from a simple recipe for making concrete from sand, gravel, cement, and water, to a complex technique for specifying proportions of materials from a vast array of available materials, additives, and admixtures, to obtain desired material properties as economically as possible. It is not surprising, then, that computer programs have been written to aid the mix designer in this difficult task. One such program has been used to develop pumpable mixes for the Al Wehdah tunnel project in Jordan, where the batch plant had several storage bins containing aggregates having different unit weights and surface moisture contents. The spreadsheet program greatly simplified the mix design process, automating some of

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[32] "Memorable Miscellany," Concrete International, October, 1979.

[33] Edward Cohen and Raymond C. Heun. "100 Years of Concrete Building Construction in the United States," Concrete International, March, 1979.

the laborious calculations that would have otherwise been necessary to solve for the mixing water and cement volumes.[34] (The solution requires an iterative approach. The spreadsheet was programmed to perform ten calculation loops every time the recalculate key was pressed, automating the calculations and making them invisible to the user.)

2.3.3 Manufacturing of Portland Cement

In Joseph Aspin's day, portland cement was processed in much the same way as it is today, albeit using manual methods rather than automated ones. It took quite awhile for the production processes to mature. Consequently, manufactured cement did not become readily available until about 1870. In 1902, Thomas Edison advanced the process technology when he made vast improvements to the rotary kiln, the primary machine used in the manufacturing of portland cement.[35]

Different varieties of cement have developed over time and are produced by altering the process parameters. Today, portland cement is produced in numerous varieties in modern, fully automated plants with centralized process control.

2.3.4 Aggregate Production

Aggregate production technology necessarily achieved rapid mechanization due to the lack of satisfactory manual production methods. In 1858, the first machine in America for the manufacturing of crushed stone was introduced.[36] Equipment used in aggregate production includes feeders, hoppers, crushers, conveyors, grading screens, washing plants, and storage bins.

Aggregate production is essentially fully automated. However, manually operated loaders, shovels, draglines, and other bulk material handling machines are used to supply the production equipment. Typically, the excavated material is loaded onto large offroad dumptrucks which carry it to the crusher plant. A new method which is

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[34] Kurt F. Peyfuss, "Simplifying Concrete Mix Design with the PC," Concrete International, December, 1990.

[35] Edward Cohen and Raymond C. Heun. "100 Years of Concrete Building Construction in the United States," Concrete International, March, 1979.

[36] Hans Straub, A History of Civil Engineering, The MIT Press, Cambridge, MA, 1964, pg 207.

gaining popularity is in-pit crushing.[37] In-pit crushing utilizes movable crushing equipment, which is loaded by material handling equipment in the quarry pit. The crushing equipment feeds the crushed stone onto conveyors, which automatically transport the material out of the pit. This new method eliminates the step of hauling the material with dumptrucks.

The two methods of producing lightweight aggregate, the rotary-kiln method and the sintering process, are also fully automated.

2.3.5 Fabrication and Placement of Reinforcing Steel

Reinforcing bars are produced in highly mechanized and automated steel mills (typical of all raw steel products). They are usually rolled and cut to 60 foot lengths. Fabrication of the rebar into desired shapes and sizes consists of bending and cutting the bars. The fabrication process has advanced from manual methods to today's mechanized methods, and will soon be automated.

Initially, all bending operations were done manually on site. Long pipes would be used to gain leverage for the bending of large bars. Bars were cut with hacksaws.[38] As the fabrication requirements became more elaborate, special rebar bending setups and mechanical bending tables were developed along with lever-action cutters and shears for cutting the bars. Soon, the operation moved from the site to specialized shops, which fabricated reinforcing steel to order. Today, fabricating shops are equipped with powered shears to cut the bars, powered mechanical bending tables, and overhead gantry cranes to move bundled bars.

The success of the mechanization of rebar fabrication has led to a great deal of interest recently in the development of automated systems for fabricating and placing reinforcing bars. In Japan, the Ohbayashi Corporation has developed a semi-automated machine for bending W-shaped reinforcing bars, a mobile, semi-

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[37] Daniel J. McConville, "Aggregate Gets Harder All The Time," ENR, October 25, 1990.

[38] A. Trevorrow, Steel Reinforcement, Construction Press, Longman, Inc., New York, 1984.

automated machine for creating U-shaped bars, and a ground assembly device for aiding the manual fabrication of reinforcing cages for beams.[39]

The Shimizu Corporation has developed a "bar arrangement" machine for placement of horizontal reinforcing bars.[40] The device operates in a manner similar to a giant pen plotter, with two degrees of freedom for finding the bar location. The bars are positioned by the machine and are tied by hand. It is interesting to note that one of the conclusions of the Shimizu development team was that it is necessary to "improve the performance of the system by incorporating an automatic tying mechanism."

Currently, development of an automated rebar bending machine is underway at the University of Maryland.[41] The proposed machine is essentially an automated mechanical bending table, with a bar feeding mechanism. It is integrated with a CAD system for input. The system is expected to reduce lead times for ordering reinforcing steel.

The development of the device proposed here for automated rebar tying is extremely propitious. Apparently, all of the required related technologies for a completely automated rebar fabrication system are reaching the culmination of development. It seems that they soon may be tied together into a fully integrated, computer controlled system.

Another approach to the improvement of rebar placing operations is off site production. A recent technological development in concrete reinforcement that has directly eliminated a major step in the construction process is the use of mat reinforcement. Prewelded reinforcing mats eliminate a large percentage of the rebar

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[39] Tatsuya Wakisaka, et. al. "Automatisation of Reinforcement Work in High-Rise Reinforced Concrete Buildings," Proceedings of the Seventh International Symposium on Robotics and Automation in Construction.

[40] Toshio Yamashita and Yoshimasa Tsuchiya, "Prefabrication of Reinforcing Bars Using CAD/CAM." Proceedings of the Seventh International Symposium on Robotics and Automation in Construction.

[41] Matthew A. Miltenberger and Leonhard E. Bernold, "CAD - Integrated Rebar Bending," Working Document to be Presented at the Seventh Conference on Computing in Civil Engineering, May 6-8, 1991.

tying process. The mats are produced with mechanized machines which bend, cut, and weld the bars into desired shapes.[42] The mats are then transported to the jobsite and are usually placed with the help of cranes.

The use of pre-manufactured mats is one approach to increasing placement efficiency, but it may not be the best approach. One problem with the approach is that a component must be designed for mesh reinforcement or the design must be converted to a mesh design. Another problem is that not every design can be fabricated into preformed mats. Only the smaller bar sizes can be used with the current production machines, so the applicability of the approach is not as widespread as for an automated rebar tying machine. In addition, even when prefabricated mats are used, some manual tying is still required. However, current use of the mats demonstrates that they are economical for some applications, and furthermore, the use of the mats demonstrates that traditional rebar tying is no longer as efficient relative to other process technologies as it used to be, and that new methods are necessary.

2.3.6 Forming Process

There have been many technological developments in the forming process. Traditional wood forms have been replaced with other materials, and modular, reusable forms are widely used. For example, plastic forms were being used by 1959 to create architectural shapes not easily obtained with traditional formwork.[43] Today, fiberglass and other plastic composites are used in forming. Steel and aluminium are often used for formwork and shoring.

Many prefabricated, factory built forms are available with patterns for different surface finishes. Most are proprietary products, with special connecting hardware. Some are specially designed to be lifted into place by crane. These so called "flying forms" allow the assembly of formwork for entire floors. Fiberboard column forms, known in the industry as Sonotubes, are widely used and greatly increase forming efficiency of round columns by eliminating the actual forming step and leaving only

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[42] Engineered Structural Mesh, Publication of Mational Wire Products Industries, Baltimore, MD.

[43] "Memorable Miscellany," Concrete International, October, 1979.

the bracing of the form. Modular forming systems are widely used for forming square columns.

The greatest example of the automation of forming, which essentially eliminates the forming process, eliminates need for scaffolding, and reduces or eliminates the finishing process, is slipforming. Slipforming utilizes a short, highly precise form that continuously moves along the work. The entire concreting operation progresses simultaneously, rather than sequentially. Slipforming eliminates a large portion of the forming process, since only a part of the structure need to be formed. In effect, the forming of the rest of the structure has been automated.

Advantages of slipforming include the elimination of construction joints, savings in reinforcement due to monolithicity, higher number of equivalent reuses of forms, high quality, high rate of progress, and economy for repetitive shapes. Disadvantages of slipforming include high initial cost of the slipform and required continuity of work, which requires workers to continue work 24 hours a day and demands higher levels of supervision, planning, and management.[44]

The first project in the United States which used slipforming techniques was the construction of a grain elevator in 1904. In 1908, E. S. Ransome patented a machine for slipforming sidewalks. In 1915, the first canal liners were slipformed by the United States Bureau of Reclamation. By 1934, rail-mounted slipformers were used for canal liner construction. Hydraulic jacks were used for vertical slipforming operations as early as 1941. In 1955, a commercially produced slipform paver become available.[45]

Today, precast floor slabs and concrete pipe are among the prefabricated slipformed products, and slipforming is used in the construction of many roads, curbs, walls, tunnel linings, and buildings.

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[44] Tudor Dinescu and Constantin Radulescu, Slip Form Techniques, Abacus Press, Kent, England, 1984.

[45] "Memorable Miscellany," Concrete International, October, 1979.

Another technological development that can be thought of as a development in formwork technology is tilt-up construction. Tilt-up construction eliminates the need for wall forms by utilizing existing slabs as a form and pouring the wall in the horizontal position. When they have cured to satisfactory strength, they are tilted up and secured. The tilt-up method of construction was pioneered in 1912 for the construction of a factory in Chicago, Illinois. Large screw jacks were used to raise the four story walls into place. Tilt-up construction technology improved over the years, allowing the construction of record sized tilt-up panels (330 ft., 2 in. by 19 ft., 11 in.) in the fifties.[46] Today, tilt-up construction is a viable approach for certain applications, and is simplified by the widespread availability of pre-engineered inserts and lifting aids.

2.3.7 Concrete Mixing Technology

Concrete mixing was one of the first mechanized operations in concrete construction. This is not surprising given the overwhelming difficulty of manual mixing. "Concreting machines" were in use in Europe by the middle of the nineteenth century. These early machines were simple rotating mixing drums.[47]

A notable American invention was the Portable Gravity Mixer, patented in 1899 by Frank Bunker Gilbreth. (Although he passed the entrance exams to MIT, Gilbreth chose to become a bricklayer's apprentice in Boston, and later went on to a successful career as a contractor, inventor, and industrial management consultant. He also achieved fame through the book and movie about his life, "Cheaper by the Dozen.") The Portable Gravity Mixer consisted of a chute with inclined rods protruding to the inside. Raw materials were fed into the top of the chute, and as they travelled to the other end, the rods forced them to mix with each other.[48]

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[46] Edward Cohen and Raymond C. Heun. "100 Years of Concrete Building Construction in the United States," Concrete International, March, 1979.

[47] "Memorable Miscellany," Concrete International, October, 1979.

[48] Jane Morley, "Frank Bunker Gilbreth's Concrete System," Concrete International, November, 1990, pp. 57-62.

In the early 1900's, concrete for paving roads was mixed in steam powered mixers. However, the raw materials were still supplied to the mixers by wheelbarrows, and the mixer location was fixed. When a batch was ready, it was dumped into horse-drawn carts, which hauled the concrete to the roadbed. By 1909, the first portable, horse-drawn mixer was introduced. In 1905, the first concrete paver was produced by powering the wheels of a concrete mixer.[49]

By 1928, the first ready-mix concrete trucks existed. The concrete was agitated by paddles which were powered by the truck's motor. The truck bodies were open, dump style bodies with semi-circular bottoms. They were equipped with hoists and chutes. The hoists lifted the body into the air, allowing the concrete to be gravity fed through the chutes to the desired location.[50] In 1941, an inclined axis, high discharge mixer was developed,[51] which became the predecessor of today's ready-mix trucks.

Today, concrete mixing is a fully automated process. Automated batch plants have been developed and are used for mass pours and in precasting yards. Materials for ready mixed concrete are automatically weighed and loaded into inclined axis trucks, which mix the concrete and deliver it to the site.

Another improvement in mixer technology is the development of fiber dispensers for mixing fiber reinforced concrete. The machines are designed to avoid the problem of "the balling up effect" which occurs during mixing if fibers are not separated when introduced into the mixer.[52]

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[49] "Memorable Miscellany," Concrete International, October, 1979.

[50] Robert E. Wilde, "70 Years of Progress: The ACI Saga," Concrete International, October, 1979.

[51] "Memorable Miscellany," Concrete International, October, 1979.

[52] R. K. Dhir and J.G.L. Munday, Advances in Concrete Slab Technology, pp. 10-11.

2.3.8 Conveying and Placement of Plastic Concrete

High labor costs in the United States in the early twentieth century provided the motivation for the development of concrete distribution and placing equipment. The early machines consisted basically of hoists, which lifted the concrete to a centrally located position, whereby it could be gravity fed through chutes to the desired locations. The discovery of the adverse strength effects of a high water/cement ratio (required to facilitate flow) led to the later developments of crane hoisting methods and pneumatic pumps.[53]

When concrete could not be placed with chutes, it was transported around the jobsite with wheelbarrows or "Georgia buggies," which are basically two wheeled, front dumping wheelbarrows. Powered buggies were soon developed to relieve the worker of the difficult task of manually buggying the concrete.

Conveyors are sometimes used to convey concrete horizontally, however, they are somewhat difficult to position quickly. Cranes in conjunction with buckets or skips can also be used to convey concrete (especially vertically) and are better for placing concrete in a desired location. However, the most flexible conveying and placing device is the concrete pump.

Although concrete was first pumped in 1909,[54] mechanical concrete pumps were not introduced to the construction industry until the thirties. These early pumps were used very little due to mechanical failures and maintenance problems.

Concrete pumps began to be used following the development of hydraulic pumps in the 1960's,[55] which were truck mounted and powerful enough to pump concrete up to 250 feet vertically, with volume flow rates of up to 45 cubic yards per hour. However, concrete pumps continued to be plagued by reliability problems and unpumpable mixes.

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[53] Hans Straub, A History of Civil Engineering, The MIT Press, Cambridge, MA, 1964, pg 207.

[54] "Memorable Miscellany," Concrete International, October, 1979.

[55] Harris, F. Modern Construction Equipment and Methods, Longman Scientific & Technical, Essex, England, 1989.

Since that time, the technology has rapidly developed. Equipment manufacturers have greatly improved the reliability and capacities of the pumps, and mix designers have learned to design pumpable mixes. For example, in 1973, concrete was pumped a record 473 feet vertically.[56] The current record is 1038 feet vertically in a single lift by the 400 hp Putzmeister TTS14000.[57] Today's pumps are capable of 1000+ vertical feet and up to 170 cubic yards per hour,[58] making them the cost effective solution for many applications. Concrete pumps have become widely accepted in the industry and are commonplace on the construction site.

Conveying and placing technologies have become highly mechanized in practice. The technologies have continued to develop, and are heading toward higher levels of automation. For example, the Fujita Corporation has developed an automated system for conveying concrete at dam construction sites.[59] The Takenaka Corporation has developed a system which mechanizes the movement of the end of a concrete pump pipe, making distribution easier by eliminating the difficult task of dragging around a heavy hose.[60]

Shotcrete is another concrete placement method that has advanced technologically. Shotcreting was reportedly first used on a house in Connecticut in 1922.[61] Although by its nature shotcreting is mechanized, the directing of the nozzle is a portion of shotcreting that has traditionally been manually performed. However, this too is becoming automated.

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[56] Edward Cohen and Raymond C. Heun. "100 Years of Concrete Building Construction in the United States," Concrete International, March, 1979.

[57] C. Terry Dooley, "Concrete Pumped 1038 ft. in Single Lift," Concrete International, October, 1989.

[58] James R. Hubbard, "Concrete Pumping Comes of Age," Concrete International, October, 1989.

[59] Akihiko Nagaoka, Toshio Mori, and Satoshi Iwaoka, "An Automatic Concrete Transit System," Proceedings of the Seventh International Symposium on Robotics in Construction.

[60] Hayao Aoyagi and Yasushi Shibata, "Development of the Horizontal Distributor for Concrete Placing," The Fifth International Symposium on Robotics in Construction, June 6-8, 1988, Tokyo, Japan.

[61] "Memorable Miscellany," Concrete International, October, 1979.

The Mitsui Construction Company has developed a shotcreting robot with a remote-controlled nozzle.[62] The Kajima Corporation has developed fully automated shotcrete robot which it has used for the construction of tunnel linings. The robot determines its position in the tunnel automatically and uses feedback control of its five degree of freedom manipulator to keep the nozzle perpendicular to the wall at a fix distance away.[63]

Another application where technological innovation in sprayed concrete has proven very successful is the placement of steel fiber-reinforced concrete. Because the steel fibers greatly reduce the flowability of plastic concrete, it is very difficult to screed off large amounts of material, so accurate placement is crucial. The manufacturers of gunite equipment have developed special nozzles for spraying fiber reinforced concrete.[64]

2.3.9 Technological Innovations in Concrete Finishing

The development of concrete finishing technology is a classic example of the evolution of concreting operations from fully manual operations to fully automated operations. In addition to the development of slipforming, which eliminates the finishing operation in some cases, there has been a transition from traditional manual methods to mechanized methods, and automated finishing systems have been developed.

Originally, concrete was consolidated, screeded, floated, and troweled manually. Mechanical vibrators were soon developed for aiding in the consolidation of concrete and were first used in 1932 for the construction of a California dam.[65] Today,

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[62] Teruhiko Umezono, Yoshito Yamada, Junichi Mihara, and Osamu Sakairi, "Development of a Concrete-Spraying Robot for Tunnel Work," The 5th International Symposium on Robotics in Construction, June 6-8, 1988, Tokyo, Japan.

[63] Hitoshi Nakajima, Kouhei Mio, Yukio Ichihara, and Yuichi Sagara, "Development of a Shotcrete Robot," The 5th International Symposium on Robotics in Construction, June 6-8, 1988, Tokyo, Japan.

[64] R. K. Dhir and J. G. L. Munday, Editors. Advances in Concrete Slab Technology, Pergammon Press, New York, 1980.

[65] "Memorable Miscellany," Concrete International, October, 1979.

vibrators and vibrating screeds are widely used in the industry. Automated concrete screeding has been developed by the Shimizu Corporation.[66] The screeding robot propels itself with wheels which ride on the reinforcing steel. The robot uses a screw auger to screed the concrete and is capable of leveling the concrete to a tolerance of plus or minus five millimeters.

Traditional manual troweling operations have also been mechanized and automated. Manually operated, gasoline powered trowels have been widely used in the industry for some time, greatly increasing the efficiency of floor finishing operations. Automated power trowels, which closely resemble the mechanized power trowels, have been developed by several Japanese companies.

The Takenaka Corporation has developed Surf Robot, a remote controlled power trowel.[67] The Shimizu Corporation has developed a similar remote controlled robot which was introduced in 1987, and which finished over two million square feet of floor area in its first year. Since then its use has been widespread.[68]

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[66] Hajime Nomura, Yasuo Kajioka, Akira Okada, and Kazumi Okuzumi, "Development of a Concrete Screeding Robot," The 5th International Symposium on Robotics in Construction, June 6-8, 1988, Tokyo, Japan.

[67] Kimio Kikuchi, Shuzo Furuta, and Takayoshi Imai, "Development and the Result of Practical Works of Concrete Floor Finishing Robot," The 5th International Symposium on Robotics in Construction, June 6-8, 1988, Tokyo, Japan.

[68] Yasuo Kajioka and Toshiaki Fujimori, "Automating Concrete Work in Japan," Concrete International, June, 1990.

2.4 Summary

This chapter has presented a snapshot of the state-of-the-art in concrete construction technology and has demonstrated how the development of concrete technology has progressed. Process technologies have been shown to be clearly moving in the direction of fully automated methods of construction. Product technologies continue to expand, increasing the suitability of concrete to different construction applications.

The focus will now shift to the second major purpose of the thesis, the prototype device for semi-automated rebar tying. The next chapter will present an analysis of rebar tying and will develop a functional definition of the task. Chapter 4 will then present the design and operation of the tool.

CHAPTER 3
ANALYSIS OF THE TASK OF REBAR TYING

3.1 Introduction to Rebar Tying

This author is by no means the first person to ponder the automation of rebar tying. There have been many attempts to create hand held machines to assist the steelworker, although no system has been adopted for use by the industry.

In Section 3.2, other methods for connecting reinforcing bars will be discussed, along with an explanation of why tying the bars with wire is the preferred connection method. The task of rebar tying will then be analyzed and discussed in section 3.3, in order to develop a list of necessary design criteria for an automated rebar tying machine. The criteria will focus on the functional requirements of the task.

In section 3.4, the designs of several patented rebar tying machines will be analyzed. The functionality of the devices will be compared with the developed design criteria, and the different mechanical methods used to achieve the desired functions will be contrasted. Chapter 4 will present the design of an improved prototype rebar tying tool.

3.2 Other Methods of Joining Rebar

Other approaches to the task of joining rebar have been attempted. These include the use of proprietary mechanical connectors (both steel and plastic), as well as the welding of the bars at intersections.

3.2.1 Clipped Connections

One type of available mechanical connector is a metal wire clip made of stiff spring steel. As shown in Figure 3-1, the fastener is preformed in the shape of a saddle. The clip is hand installed around two perpendicularly placed bars, allowing the rigidity of the steel to hold the bars together.[69]

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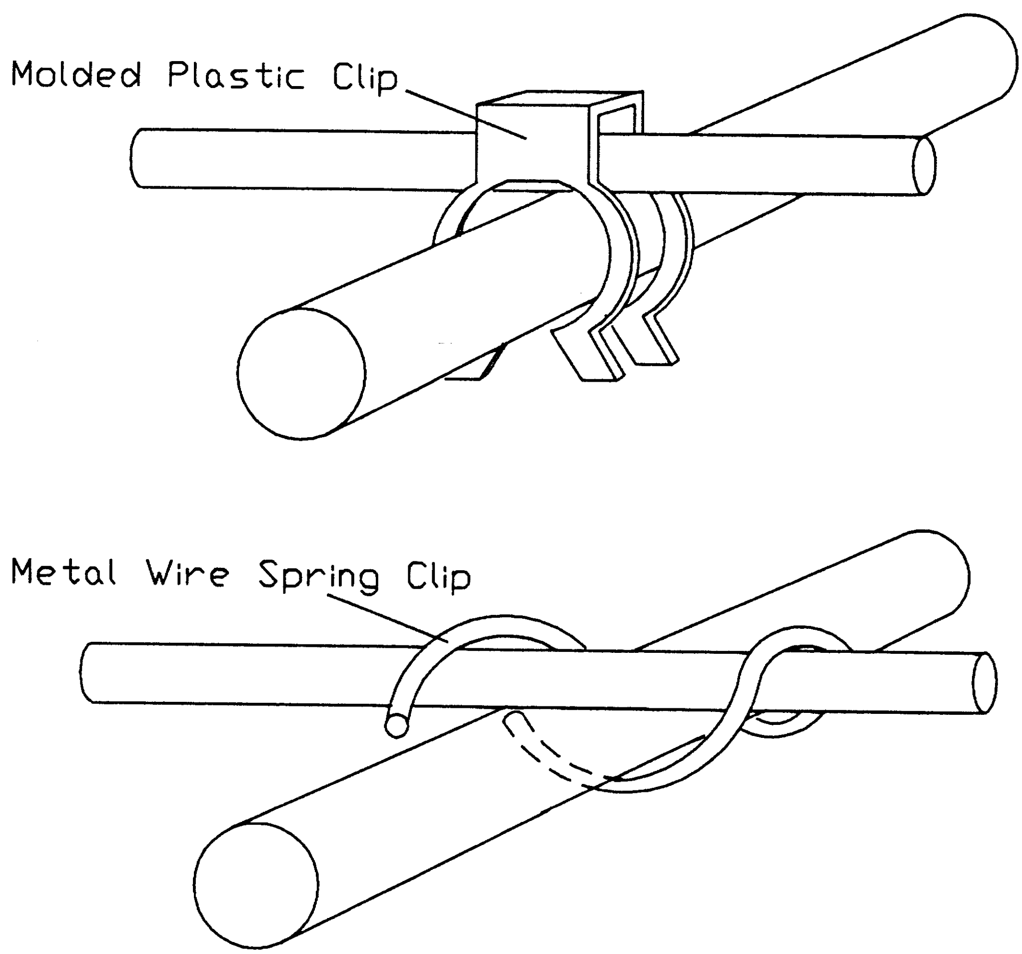
[69] A. Trevorrow, Steel Reinforcement, Construction Press, London, U.K., 1984.

Figure 3 - 1

Clipped Connections



Another available proprietary connector is a molded plastic clip for joining two perpendicular bars. As shown in Figure 3-1, the clip fits over the top bar and clips to the bottom one.[70] These connectors, as well as the metal clips described above, are removable and reusable in the event that the steel must be disassembled.

One problem with the clip schemes is that different sizes of clips are needed for different sizes of rebar. In addition, the clips are only designed for joining perpendicular bars, and do not produce sufficiently tight connections.

3.2.2 Welded Connections

Welding of reinforcing bars, while an obvious possible solution, is not normally done except for some lap splices. "Tack" welding should never be used because it can reduce the strength of the bars by 50 percent.[71] ACI 318-83, Building Code Requirements for Reinforced Concrete, states in section 7.5.4 that "Welding is not permitted for assembly (of the rebar) unless authorized by the engineer." The justification of this statement is found in the corresponding section of the commentary which states, "Tack welding can seriously weaken a bar by creating a metallurgical notch effect." However, the commentary also contends that "The operation can be performed safely..." if done in a controlled environment, as in the case of welded wire fabric.

In a study done at the University of Maryland, welded rebar mats were used for primary flexural reinforcement of slabs. Some of the sections underwent a sudden, premature, brittle failure when the longitudinal bars fractured at weld points. This study dramatically showed the potentially harmful effects of metallurgical notches that occur in poor quality welded connections.

Butt welding of splices is sometimes done to save the extra steel required for the lap length, especially for the larger bar sizes. This can be done safely, with a properly welded splice being capable of developing the full yield strength of the steel bars. Full depth welds are required. In a traditionally tied lap splice, the concrete forms

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[70] "Rebar Fasteners," Concrete International, February, 1989, pg. 96.

[71] Joseph J. Waddell, Editor, Concrete Construction Handbook, McGraw-Hill, New York, 1968.

the splice, with no requirement for the ties to carry load.

3.3 Functional Description and Requirements for the Task of Rebar Tying

In defining the task of rebar tying, it is useful to determine:

- What is the purpose of the connection?
- What regulations or codes (if any) govern the connection?
- How many different types of connections are required?
- To what extent will there be interference from other bars or formwork?
- How many different tying methods are currently used?
- What are the types and properties of standard tie wire?

3.3.1 Purpose of the Connection

The sole purpose of the connection is to fix the relative positions of the reinforcing bars during the construction operations. There is no structural capacity required of the connection, other than the support of loads which may occur before and during the casting of the concrete.[72]

It is not necessary that every bar intersection be tied, since the ties do not contribute to the strength of the cured concrete.[73] However, a sufficient number of intersections must be tied to keep the steel from moving. This number is based on the configuration of the bars and knowledge of the proposed concrete placing method, and is determined by judgement. For example, many more intersections must be tied for retaining wall reinforcing steel that will have concrete pumped into place than for flat slab reinforcing steel that will have concrete placed with a conveyor.
The first design criteria for an automated rebar tying machine is the ability to produce a strong, tight tie, capable of keeping the reinforcing steel from moving during construction. The expected loads that must be resisted include the dynamic action of pumped liquid concrete and the weight of workers.

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[72] American Concrete Institute, Publication SP-2, Manual of Concrete Inspection, 1975.

[73] Joseph J. Waddell, Editor, Concrete Construction Handbook, McGraw-Hill, New York, 1968.

3.3.2 Code Requirements

There are no standardized, codified requirements for tying rebar. There are only vague, functional requirements that imply that the rebar must stay in place during construction. There are no expressly prohibited methods of joining the bars except for tack welding. However, how many or what percentage of the intersections must be tied is sometimes prescribed in local codes. For example, in the Washington D.C. area, 100% of the intersections in the top layer of steel for bridge decks must be tied, and 50% of all other layers. Usually, the architect or engineer will specify what percentage of intersections must be tied on the plans.

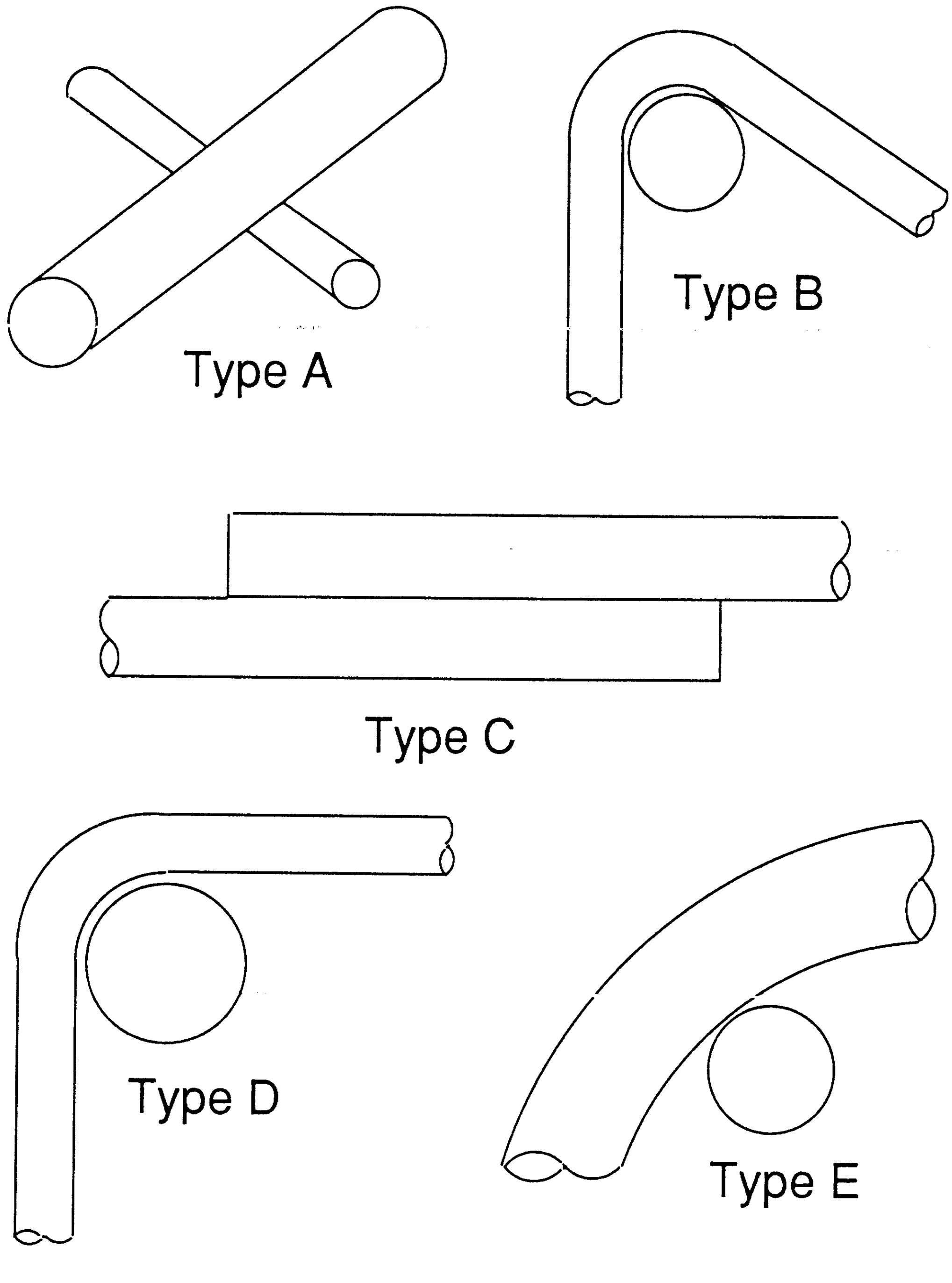
3.3.3 Required Types of Connections

There are many different configurations of rebar which must be considered. Figure 3-2 shows details of five common types. Type A is a perpendicular intersection of two bars, a very common configuration in slabs and walls. Type B is a bar intersecting a hooked bar. Type C is a lap splice. Type D is a bar intersecting a 90 degree bent bar, commonly found in beams and rectangular columns. Type E is a bar intersecting a curved bar, as found in round columns. Although other configurations are possible, most are variations of these five types.

In the cases with curved or bent bars, typically the perpendicular bar is placed on the inside of the curved bar, and is often larger in diameter. Any of the described connections can contain different sized bars. Bar sizes range from .375 inches in diameter for a number three bar to 2.257 inches in diameter for a number eighteen bar.

The second design criteria for the rebar tying machine is the flexibility to create a tie for many different configurations of bars, over a range of bar sizes.

Figure 3 - 2 Connection Types



3.3.4 Interference

Interference can be encountered from different sources. In order to loop the ties around the bars, an automated rebar tying machine may have to reach past the bars (so does a steelworker). In doing so, the tool may be interfered with by adjacent bars or by a lower layer of bars that is beneath the surface of the work. The required minimum clear distance between layers is only one inch.[74] Interference also may occur from bar supports, spacers, formwork, or the ground.

The most constraining interference may occur for the bottom layer of bars in slabs not exposed to weather or in contact with the ground. Minimum cover required for reinforcing steel under these conditions is .75 inches. Therefore, there may be only .75 inches between the bottom of the steel and the formwork.

Interference from closely spaced adjacent bars would probably occur at greater than two inches, since any closer spacing of the steel would make concrete placement and consolidation difficult. However, the minimum clear spacing allowed between adjacent bars is the larger of the bar diameter and one inch, so it would be preferred to have a design distance of one inch.

The third criteria for the tying machine is the ability to operate within certain interference constraints. The desired design distances are .75 inches below and 1 inch on the sides, although a slightly larger side distance would be acceptable.

3.3.5 Joining Rebar With Tie Wire

The most common method for joining rebar has been to tie the bar intersections with wire.[75] The five most common types of "knots," as shown in Figure 3-3, are the diagonal tie (also known as the "snap" tie), the saddle tie, the crossed saddle tie, the figure eight, and the splice tie. The saddle tie, the crossed saddle tie, and the figure eight tie are the most stable and least likely to slip of the ties, with the diagonal tie being the least secure.

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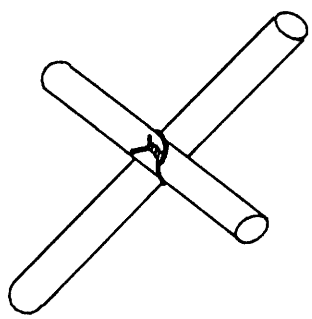
[74] The American Concrete Institute, ACI 318-83, Building Code Requirements for Reinforced Concrete, 1983.

[75] Joseph J. Waddell, Editor, Concrete Construction Handbook, McGraw-Hill, New York, 1968.

Figure 3 - 3

Types of Ties



Diagonal Tie

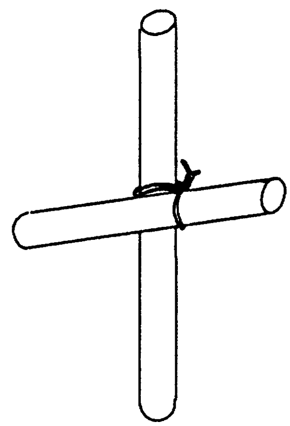
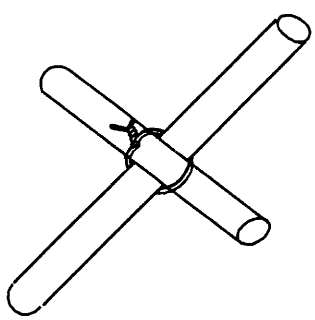
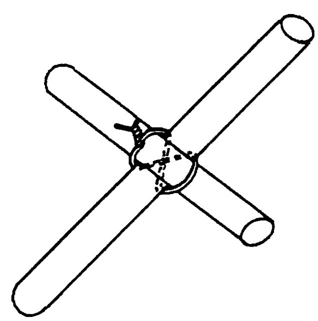


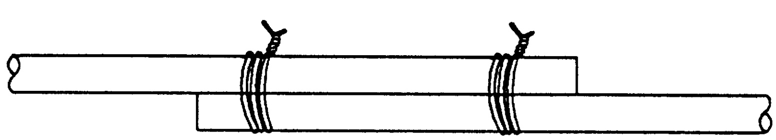
Figure Eight Tie



Saddle Tie



Crossed Saddle Tie



Splice Tie

The choice of which tying method to use is largely up to the individual worker, but it depends on the type of connection. For flatwork, the diagonal tie is satisfactory, but some workers prefer to tie saddle ties for every connection. When securing horizontal bars to vertical bars in a wall, for example, and for bent bar connections, one of the saddle tie variations is required, since a diagonal tie will slip. The choice of which saddle tie method to use is entirely up to the preference of the worker. If workers will need to climb up the steel, as in tall columns and walls that are tied in place, the figure eight tie is usually used.

It is fair to say that the two saddle tie methods and the figure eight tie are preferable, since they provide a more secure connection, but diagonal ties are used when possible because they are generally easier and faster for most workers to tie. Although not a functional design criteria, it would be preferred that the rebar tying machine be capable of producing a saddle tie or figure eight tie, since they are higher quality and much more stable ties than the diagonal tie.

3.3.6 Physical Characteristics of Tie Wire

Usually 14 gage or 16 gage wire is used to tie rebar,[76] with 18 gage being the smallest recommended size.[77] For size nine bars and larger, workers will usually use two strands of 16 gage wire.

American Wire Tie, Inc., markets double loop wire ties in gage 12 through gage 19. These ties consist of straight wires with preformed loops on each end. The ties are available in lengths of three inches to three feet. Hand powered tying tools which are used with these ties hook the two loops and twist them. Figure 3-4 shows the widely available forms of tie wire and commonly used, hand-powered, tying tools.

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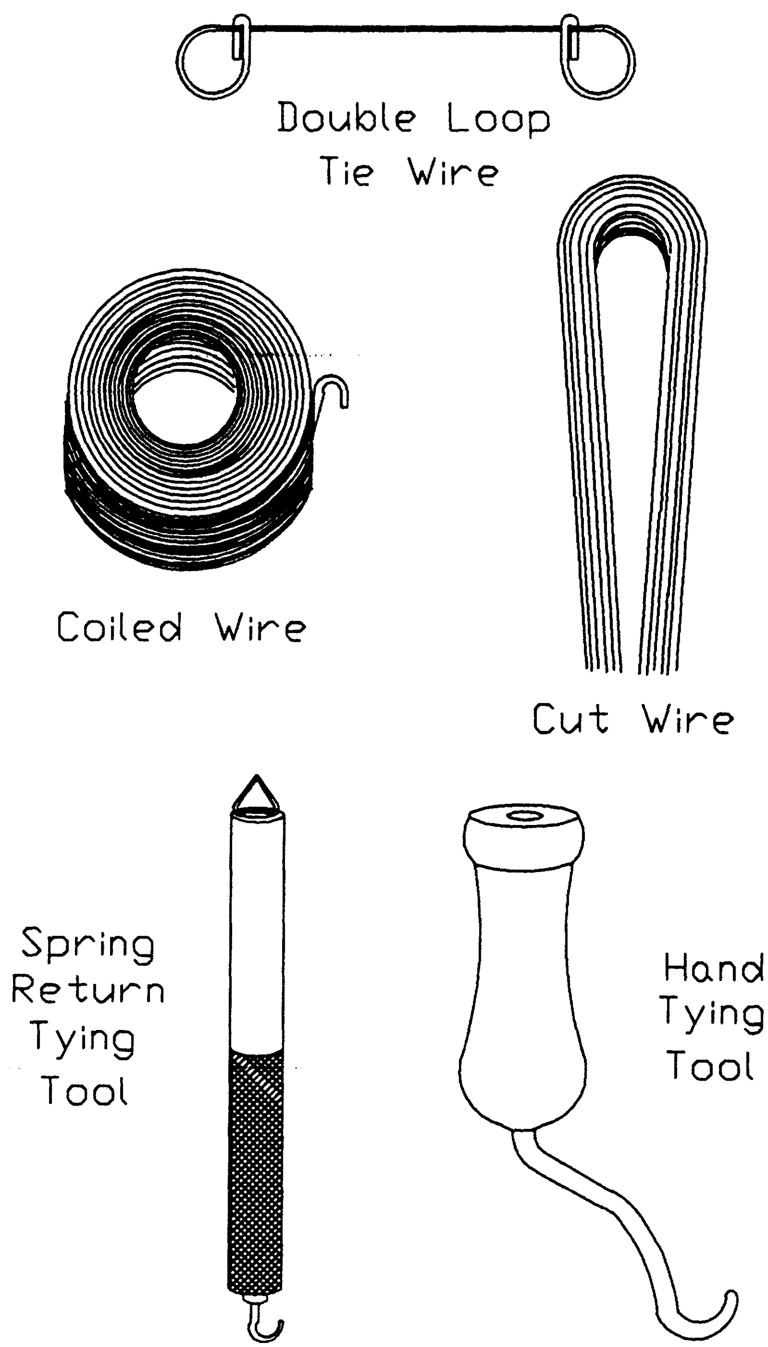
[76] Joseph J. Waddell, Editor, Concrete Construction Handbook, McGraw-Hill, New York, 1968.

[77] The American Concrete Institute, ACI 318-83, Building Code Requirements for Reinforced Concrete, 1983.

Figure 3 - 4

Tie Wire and Twisting Tools



Tie wire is usually soft, annealed wire that is tough but pliable. It is available with a galvanized or P.V.C. coating for use with galvanized and epoxy-coated rebar. Galvanized wire should not be used to tie galvanized rebar, nor should uncoated wire be used with epoxy-coated rebar. Acceptable coatings are nylon, epoxy, or vinyl.

Another form of wire marketed by American Wire Tie for tying rebar is coiled wire. The wire comes in 3.5 pound coils, and is available in gage 14 through gage 18. The most commonly used coiled wire is soft, black, annealed wire, but it is also available with a galvanized coating, with a P.V.C. or nylon coating, and in stainless steel. The spools of wire are carried on the worker's belt in a special reel. The worker uses pliers to cut and twist the wire.

Each form of tie wire has advantages and disadvantages. The coiled wire is less expensive and can be cut to different lengths for tying different sized bars. The double loop wire ties must be bought in different sizes, since short ties cannot be used for large bars and long ties are wasteful and clumsy for tying small bars. The double loop wire ties allow inexperienced or unskilled laborers to tie rebar quickly, but workers skilled in rebar tying can work just as fast or faster with the coiled wire, and usually prefer to use it.

The final functional design criteria for the rebar tying machine is the ability to create ties with coated and uncoated wires. The wire size should be within the acceptable range of gauge 14 to gauge 18.

3.3.7 Further Design Criteria

There are three additional design criteria that arise from practice. The first one is the ability to operate the machine from a standing position. One of the motivations of automating construction is to reduce the backbreaking work that is required. Rebar tying is particularly difficult, since workers must be bent over for long periods of time. In many cases, this results in back disorders.

The second additional design criteria is speed. Speed is important because it is integrally related to the economics of the operation. Since 90% of all rebar placement work is subcontracted, the driving interest is price. If a subcontractor cannot produce work at a competitive price while using the device, then he will not use it.

The potential benefits of an automated tying machine are the improvement in consistency and quality which is ultimately realized by the owner, and the improvement in worker health. It is not likely or desirable that the owner will be willing to pay more money or that the worker will be willing to take a cut in pay. Although the device should allow the use of lower skilled workers for the task, this savings should not be offset by the need to use more workers to complete the task timely.

A successful tying device should be as fast as an average worker, allowing an overall reduction in the cost of the task by use of lower skilled workers, as well as improved quality and worker health. Union steelworkers average between fifteen and thirty diagonal ties per minute. Therefore, the device must be able to complete a tie in approximately two seconds.

The last design criteria is durability. The construction environment is extremely harsh. Tools are routinely exposed to rain, dirt, dust, extreme heat, extreme cold, rough handling, vibration, shocks, etc., so a tool must be designed accordingly.

3.4 Analysis of Previous Embodiments

The summary of the seven criteria with which to judge the following patented devices are:

- the speed of operation
- the ability to make a tight tie
- the ability to tie different configurations of rebar
- the ability to operate in the presence of interference from the sides and below
- the ability to tie a saddle tie or figure eight tie
- the ability to use coated as well as uncoated wire
- the ability to be operated from a standing position
- durability in the construction environment

Several different patented devices were found that were specifically designed to tie rebar. Other similar wire tying devices (such as a machine to form bread ties) were also analyzed. No device met all of the criteria listed above, but many of the devices satisfied certain criteria extremely well, with some very well designed components.

The analysis will proceed with the detailed discussion of each design criteria, and of what is required of the device to satisfy the criteria. The reviewed patented inventions will be referred to by the inventor's last name, and will be used to illustrate a particularly good or bad approach to a component's design. If more than one inventor is listed, the first inventor's name will be used. The list of patents and their inventors is given in Appendix 3 as a reference for use while reading the following analysis.

3.4.1 Type of Tie / Configuration of Bars

The ability to tie different configurations of rebar is intrinsically bound to the type of tie that a device is capable of tying. Diagonal ties can be used for Type A and Type C connections as defined in Figure 3-2, but saddle ties are required for Type B, D, and E connections.

Of the devices analyzed, only the Huerta system attempts to tie a saddle tie. Every other device ties a diagonal tie. However, the Huerta device is not a saddle tying device, but rather a system in which a preformed saddle tie is applied to the bars by hand, and a device is used to clamp the ends and twist them. In effect, it is a power driven pliers. Therefore, it seems that no device is capable of satisfying the criteria of connecting different configurations of rebar, or of making the higher quality saddle tie.

3.4.2 Type of Tie Wire

It seems that every device had the ability to use coated as well as uncoated wire, although none of the patents expressly mentioned coated wire. The important consideration in the use of coated wire is the twisting mechanism, since coated wires tend to rebound more, making a tight tie more difficult to obtain.

All the devices except one used continuously supplied wire. Most used built-in spools of wire, but some had external, continuous supplies, such as a spool on the worker's belt. In contrast, the Hanigan device used preformed staples, which it placed over the bars diagonally. It then attempted to twist the ends of the staple together below the bars.

The wire feeding mechanisms were all variations of a wheel or roller driven scheme, a very common method of feeding wire (except for the Hanigan stapler). Most were very similar in design.

3.4.3 The Ability to Make a Tight Tie

It is crucial that the device be capable of producing a tight tie. Analysis of the patented devices shows that very few of the machines were capable of a tight tie. In fact, many of them mention the impotence of previous embodiments in this matter.

To make a tight tie, the wire must form the shortest path around the bars. Basically, the wire should lie along the convex hull of the intersection. To force the wire to do this requires that there be enough tension on the ends of the wire before twisting and during the initial twisting motion to pull it tight around the different sized bars.

The Muguruma and the Geiger devices are capable of this, but the Muguruma device relies on the operator to pull on the device to create this tension. The Geiger device not only grips the wires, but also pulls on them while it twists them. The mechanism it uses will be described in more detail, since this is the only device which satisfactorily accomplishes this extremely important design objective.

The Geiger device contains an integrated gripping and twisting mechanism. It grips the ends of the wire by pinching them between a fixed member attached to the gripping-twisting mechanism and a spring mounted member attached to the frame. It then retracts the entire mechanism pneumatically, as it begins to twist the wires.

3.4.4 Bar Sizes / Interference

A tradeoff exists between the ability to tie a great many bar sizes and the ability to operate in the presence of interference from the sides and below. Since the largest bar diameter is six times as great as the smallest, a device designed to accommodate the larger bar sizes is bound to have problems with smaller bars. It will encounter interference and perhaps will have other problems.

The Furlong device is the only one that explicitly addresses this problem. It incorporates an adjustable wire feed mechanism capable of feeding two different lengths of wire, and suggests that there be two sizes of end .

3.4.5 Operation While Standing

The ability to be operated from a standing position is a very important design criteria. Most of the devices are capable of remote operation, or could be easily adapted to it. One desirable feature in a rebar tying device is the capability of quickly switching between remote and close use. This would enable the worker to use the same tool comfortably on walls and slabs.

3.4.6 Durability

As mentioned above, the construction environment is very harsh. Many of the devices obviously are not suited for the conditions they will encounter. Very simply put, a well designed machine for construction should not have exposed intricate components.

3.4.7 Speed

Speed is quite probably the most important design criteria of the machine. The speed of operation will ultimately decide the success or failure of the machine. None of the patents mention the cycle time of the device. A good design will minimize the number and duration of serial operations.

CHAPTER FOUR
DESIGN OF AN IMPROVED REBAR TYING MECHANISM

4.1 Introduction to the Design of the Device

This chapter presents the design of a prototype rebar tying machine. In Section 4.2, the overall design of the tool will be described in terms of the functional requirements of the task that were enumerated in the previous chapter. The operation of the tool will be demonstrated with schematic diagrams in Figures 4 - 3 through 4 - 10 of Section 4.3. Sections 4.4 and 4.5 will present detailed designs of key components of the device.

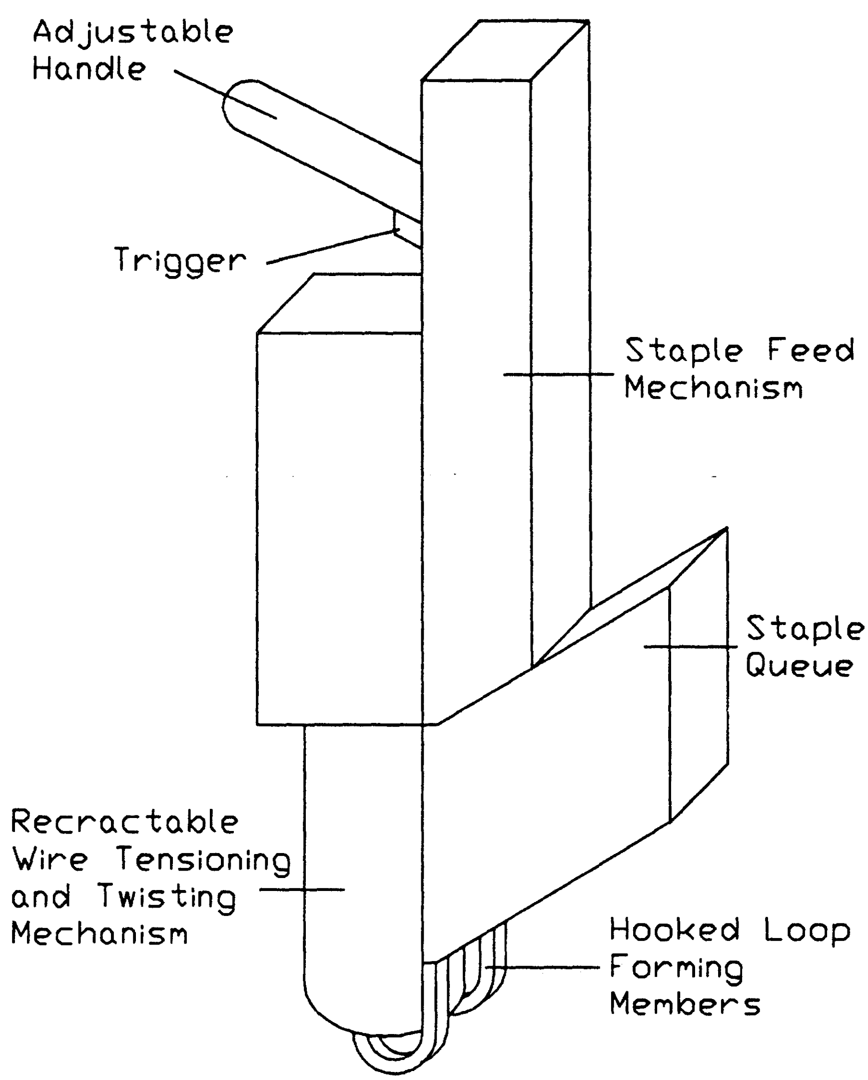
4.2 Overall Design of the Device

A schematic drawing showing an isometric view of the prototype tool is provided in Figure 4 -1. The machine is a hand held tool that will allow a worker to tie rebar from a standing position. The worker will position the tool such that the hooked loop forming members at the far end of the tool are positioned at the intersection of the bars and around the lower bars. The worker will then pull a trigger, and the device will automatically initiate a series of actions resulting in a tied connection.

The tool is designed to tie saddle ties. To tie a saddle tie at the intersection of two perpendicularly placed bars, for example, the machine must be able to loop the wires under the bottom bar on each side of the top bar and over the top bar on either side of the bottom bar. This can be seen clearly in Figure 3 - 3. A worker accomplishes this task easily with the aid of dexterous fingers. The tool presented here accomplishes the task by placing a "u" shaped wire over the top bar on one side of the bottom bar, forcing the wire to loop around the bottom bar on each side of the top bar, and joining the two ends of the "u" shaped wire above the other side of the top bar.

Figure 4 - 1

Prototype Rebar Tying Tool



The major components of the device, labelled in Figure 4 - 1, are the staple feed mechanism and the retractable wire tensioning and twisting mechanism. For the purpose of this discussion, the top bar will be defined as the bar that is closer to the tool, with the bottom bar referring to the bar that is farther from the tool. The "u" shaped wire will be referred to as a tie, a staple, or a staple tie.

The staple feed mechanism acts to push a tie from the staple queue, which is angled away from the end of the tool to provide maximum clearance from interference at the end of the tool. The tie loops over the top bar on one side of the bottom bar. The ends of the tie are forced through the two hooked loop forming members which force them to bend around the bottom bar on each side of the top bar. The cylindrically shaped retractable wire tensioning and twisting mechanism then secures the ends of the tie and joins them on the other side of the top bar by twisting them together. The operation of the tool is provided in more detail later in the chapter.

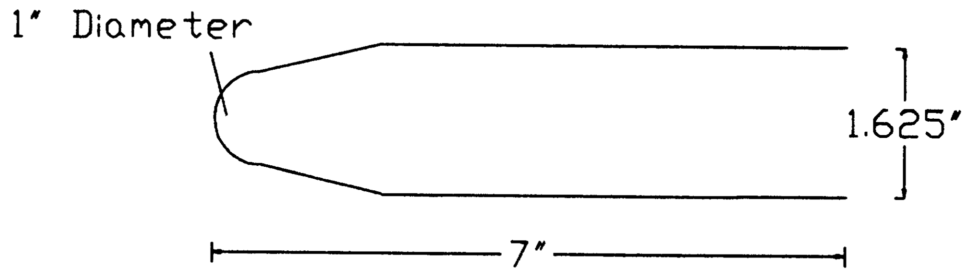
4.2.1 Type of Tie / Configuration of Bars

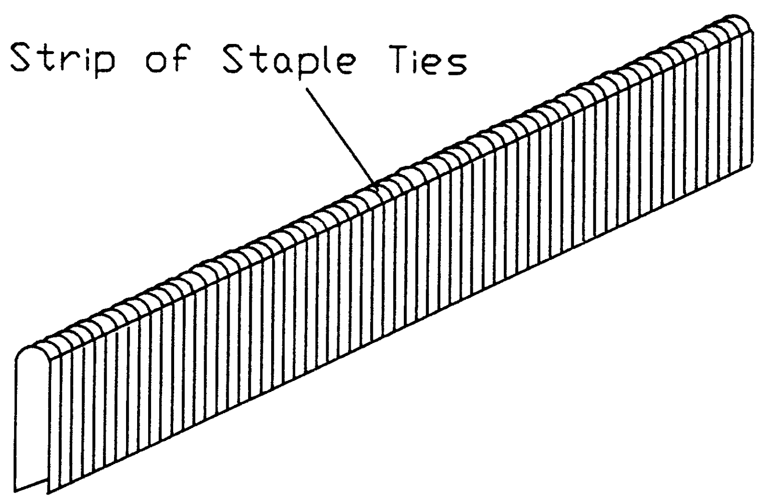
Since the tool is designed to produce saddle ties, it can be used to tie bars configured like Type A, B, D, and E of Figure 3-2, but not like Type C. Three factors led to the choice of the saddle tie. The saddle tie is a good choice of tie because of its applicability to a wide range of configurations of bars. Also, the bars are less likely to move when tied with a saddle tie than with a diagonal tie, resulting in a higher quality connection. Finally, since the connection is higher quality, a lower percentage of connections may need to be tied, resulting in a reduction in the amount of work required and a proportional reduction in cost.

In light of the above advantages, it is surprising that none of the previously patented devices have attempted to create saddle ties, especially since the saddle tie has many of the same design considerations as a diagonal tie. For example, it is necessary in both cases to form a loop of the wire around the bars. In both cases it is also necessary to grab the ends of the wires to twist them. However, the saddle tie does require some additional considerations. For example, the problem of interference is greater, since two loops must be formed around the bars simultaneously.

Figure 4 - 2

Prototype Staple Tie Geometry





4.2.2 Type of Tie Wire

The tie wire used will be the same type of annealed steel wire as traditional tie wire. It will be premanufactured into strips of staples, shaped as shown in Figure 4 - 2. The overall length will be seven inches and they will be 1.625 inches wide, the same width as the center to center distance between the guide grooves of the hooked loop forming members. The tops of the staples are formed with a one inch radius, providing a close fit to the largest bar size that the device is designed to handle. The staples will be available in coated and uncoated wire, to allow the use of the device for coated and uncoated bars.

4.2.3 The Ability to Make a Tight Tie

The design of the device focuses on the requirement that the tie be tight. The tying mechanism ensures a tight tie through its unique tensioning and twisting action. The ends of the wire are first pulled tight, to ensure that the wires are tightly formed around the bars, and to remove any slack that is in the tie. A twisting bar is then extended that ensures that the first crossing of the wires occurs just above the top bar. While the twisting occurs, the twisting bar remains in its extended position and tension continues to be applied to the wires, resulting in a tight tie every time.

4.2.4 Bar Sizes / Interference

The device will be capable of handling bar sizes ranging from size three to size eight. The ability to accommodate some range of bar sizes is essential, since in practice many different combinations of bar sizes will be encountered. However, the entire range of bar sizes is too great to be encompassed in one device with the current design. The range of sizes from three through eight is the most practical subset of the range, since for larger bars, double strands of tie wire are traditionally often used.

The tool will be able to operate with clearances of 3/4 inch below and 2.125 inches on the sides. Although it is desirable to have a clearance of one inch on the sides (the minimum distance allowed in the building code), other design requirements make that distance virtually impossible to achieve. If the hooked loop forming members were capable of lateral motion (to move closer together and farther apart), the tool could operate within the minimum distance for the lateral spacing between parallel top bars, but it would have required a more complex tool design. At least one more actuator would have been required, and the use of a preformed staple would have been impossible. The device would have had to a use two continuous spools of wire, requiring that both sides of the saddle be tied and requiring the addition of a wire cutting mechanism. Since the hooked loop forming members have a diameter greater than the minimum distance, it would be impossible to operate perpendicular to the top bars within the minimum distance without either using flexible loop forming members or an unguided loop former. Both methods would have reduced reliability and made the task of avoiding interference from below more difficult and unpredictable.

4.2.5 Operation While Standing, Durability and Speed

Standing operation, durability, and speed are the remaining design requirements of the device. The device is specifically designed to be used from a standing position, with an adjustable handle enabling comfortable use by workers of different heights. The cycle time of the tying operation, from initial triggering to return to ready position, is two seconds. All actuators will be designed to achieve the necessary accelerations. The device will be capable of surviving the harsh construction environment, with most of the mechanisms enclosed within the device.

4.3 Operation of the Device

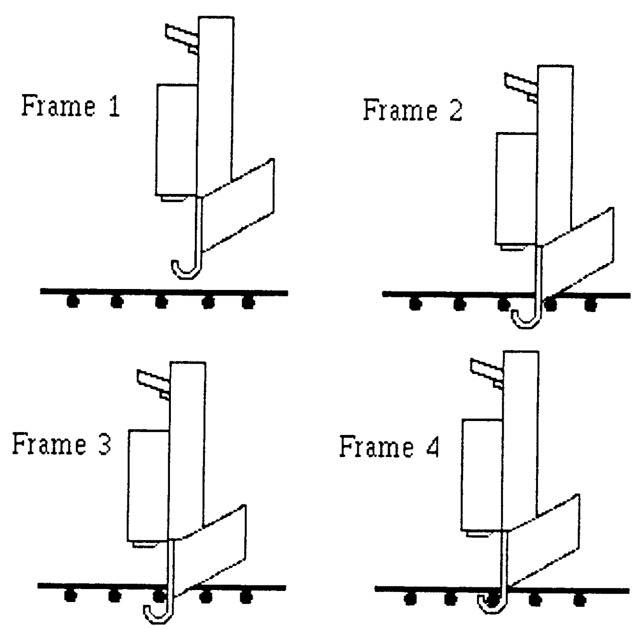
The complete step by step description of how the worker uses the device to accomplish the task will be illustrated now with several schematic diagrams. The operation of the two major components of the design, the staple feeding mechanism and the retractable wire tensioning and twisting mechanism, will be described in the context of the eight steps which compose the tying operation, shown graphically in Figures 4 - 3 through 4 - 10.

4.3.1 Step One - Positioning

The first step in the tying operation is performed by the worker, as shown in Figure 4 - 3. The worker must position the device so that the hooked loop forming members are below the lower bar. This will typically entail the lowering of the device while the two hooked loop forming members straddle the top bar and are between the rows of bottom bars, as shown in the first two frames of figure 4 - 3. The third frame of Figure 4 - 3 shows how the loop forming members are then translated in the direction of the open side of the loop. Once the hooked loop forming members are beneath the lower bar, the worker then lifts up the device, positioning the lower bar firmly in the loop forming members, as in the fourth frame of Figure 4 - 3.

When the minimum interference below the bars is encountered, the worker can rotate the device into position, so that the hooked loop forming members can pass beneath the device while avoiding the interference. Now that the device is positioned, the worker must simply press the start button to actuate the series of tying steps.

Figure 4 - 3
Step One - Positioning



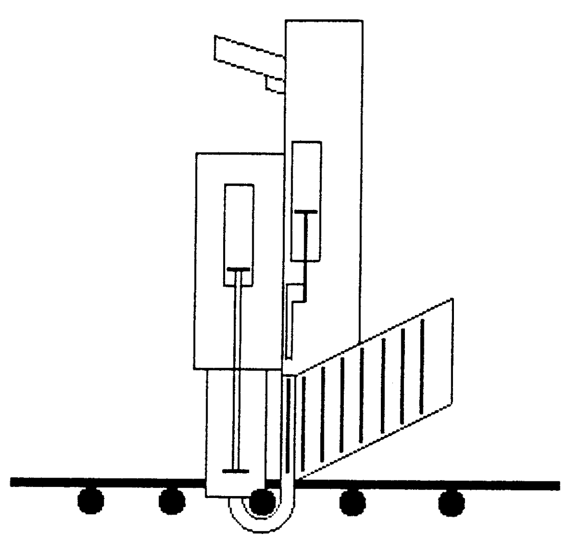
4.3.2 Step Two - Lowering of Tensioning and Twisting Mechanism

Step two of the tying operation is the lowering of the retractable wire tensioning and twisting mechanism. This mechanism is originally in the fully retracted position, so it does not interfere with the positioning operation. The cylindrical member is lowered into the fully extended position, placing it in contact with the hooked loop forming members. The bottom of the member contains two wire receiving holes which are needed to guide the ends of the staple tie into the wire holding mechanism. These holes are aligned with the grooves of the hooked loop forming members when the tensioning and twisting mechanism is in the extended position. The tensioning and twisting mechanism is now in position to receive the ends of the staple.

Simultaneously, the retractable twisting bar is lowered until it contacts the top reinforcing bar. The twisting bar consists of a cylindrical tube coaxial with and centered on the retractable tensioning and twisting mechanism. Perpendicular to the tube at the end is a bar which has the function of forcing the wires to cross at the surface of the top bar when they are twisted.

Figure 4 - 4

Step Two - Lower Twisting Mechanism

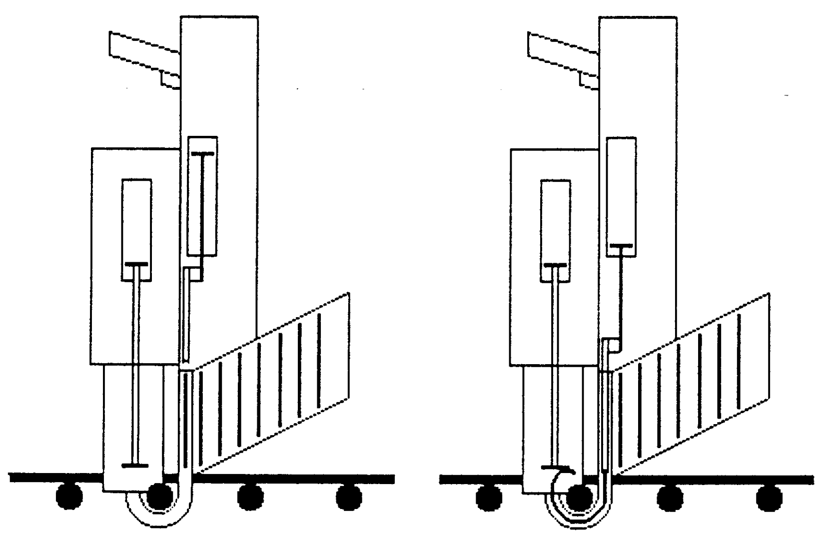


4.3.3 Step Three - Staple Feeding

The feeding mechanism consists of a linear pneumatic actuator and a feeding member that is shaped to conform to the shape of the top of the staple tie. The actuator forces the feeding member downward, pushing the first wire staple in the queue downward through guide grooves and through the two grooves in the hooked loop forming members. The semi-circular loop forming members permanently deform the wires, forcing them to curve around the bars. Since the wires are permanently deformed, the ends continue to move in a circular path into the receiving holes of the wire holding mechanism. Once the ends of the staple have proceeded through the loop and into the wire holding mechanism, the feeding mechanism stops.

Figure 4 - 5

Step Three - Staple Feeding

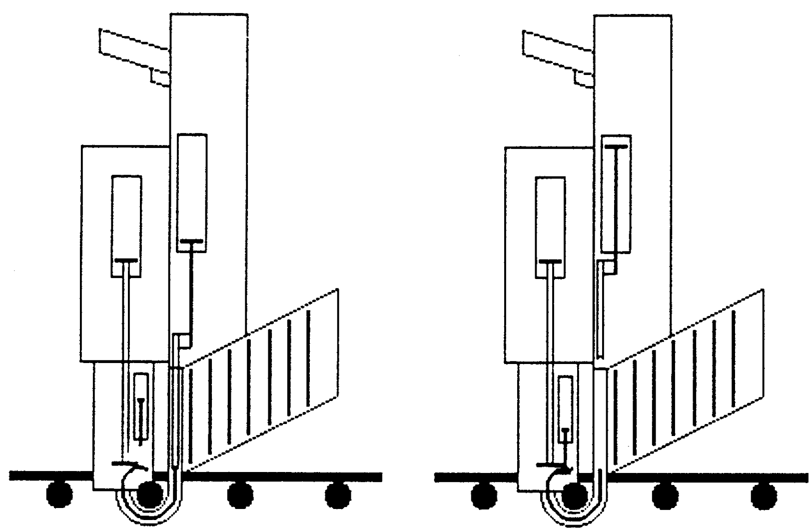


4.3.4 Step Four - Grabbing the Ends of the Wire

The ends of the wire are now in position to be held tightly. The wire holding mechanism contains two pneumatically powered rods which are moved axially within guide holes. Each rod presses an end of the wire tie tightly into the wire holding mechanism, deforming the wire around the wire holding anvils and thus firmly gripping the ends of the wires.

Figure 4 - 6

Step Four - Secure Ends of Staple

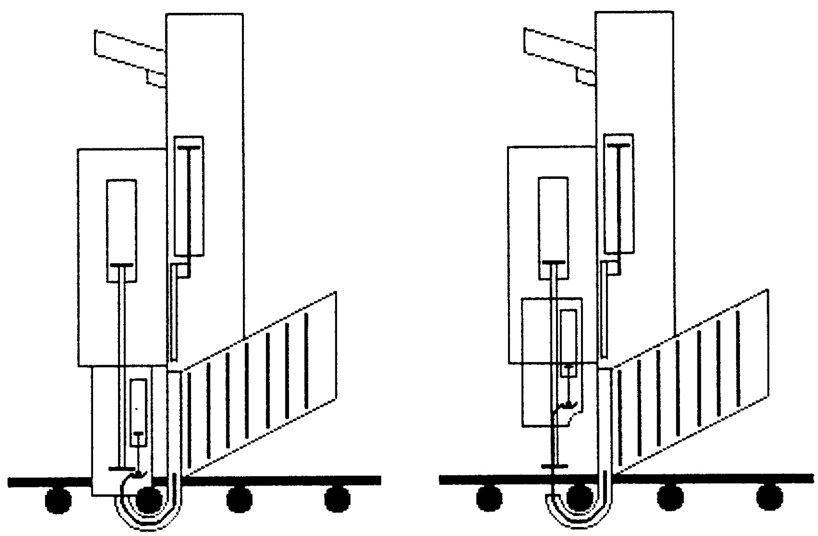


4.3.5 Step Five - Retracting the Tensioning and Twisting Mechanism

The tensioning and twisting mechanism is then pneumatically retracted with a constant force, pulling the staple tightly around the bars and removing any slack in the wires. The twisting bar remains in the extended position, however, since it must be near the top of the top bar during twisting to ensure that the tie is tight.

Figure 4 - 7

Step Five - Retract Twisting Mechanism

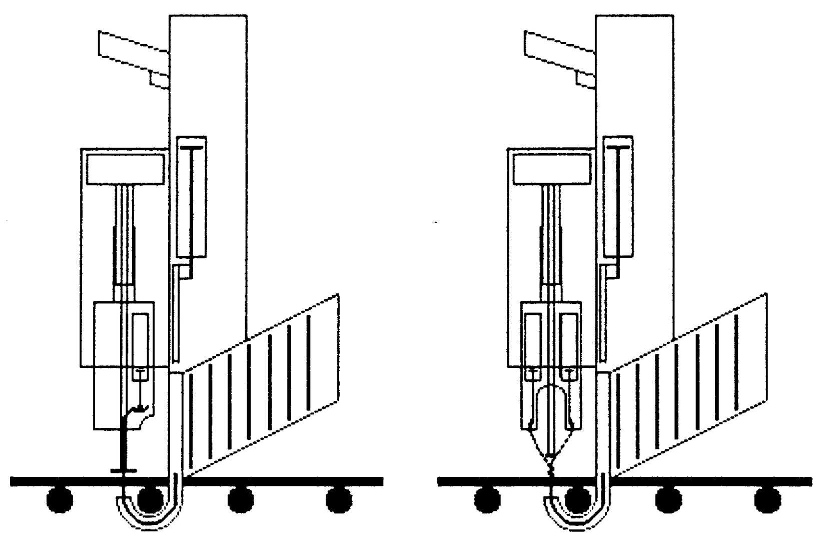


4.3.6 Step Six - Twisting the Wire Tie

When the wires have been pulled tight, the tensioning and twisting mechanism is then rotated a predetermined number of times by a pneumatic rotary actuator, twisting the ends of the wires together. During the twisting operation, the tensioning and twisting mechanism continues to be forcibly retracted, keeping tension on the wires. Since it is retracted with a constant force, the twisting and tying mechanism will move downward slightly as the free length of the wire shortens from the twisting operation.

Figure 4 - 8

Step Six - Twisting the Tie



The deployed twisting bar ensures that the first crossing of the wires occurs at the top of the top reinforcing bar. The twisting bar must rotate with the tensioning and twisting mechanism. If only the twisting bar rotated, the wire would be twisted in opposite directions on each side of the twisting bar. If the twisting bar remained stationary, the wire would be twisted above the twisting bar.

4.3.7 Step Seven - Wire Released

The tie has been created, and the ends of the wire tie are released by the wire holding mechanism.

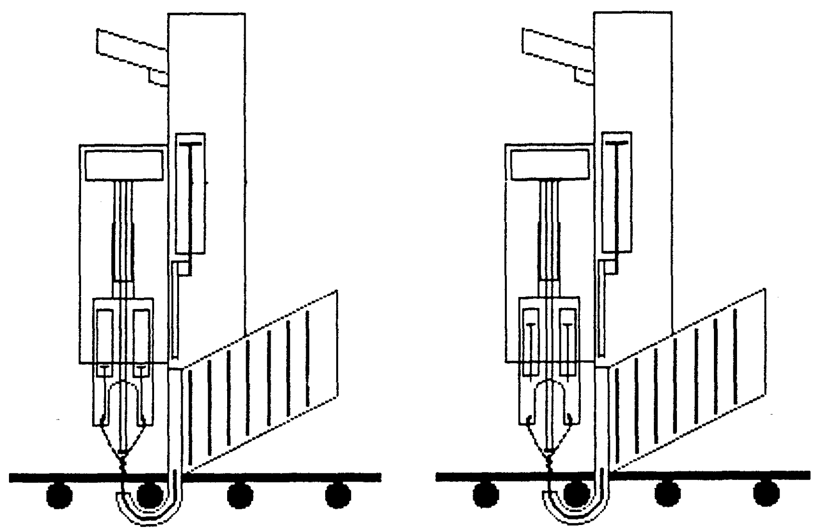


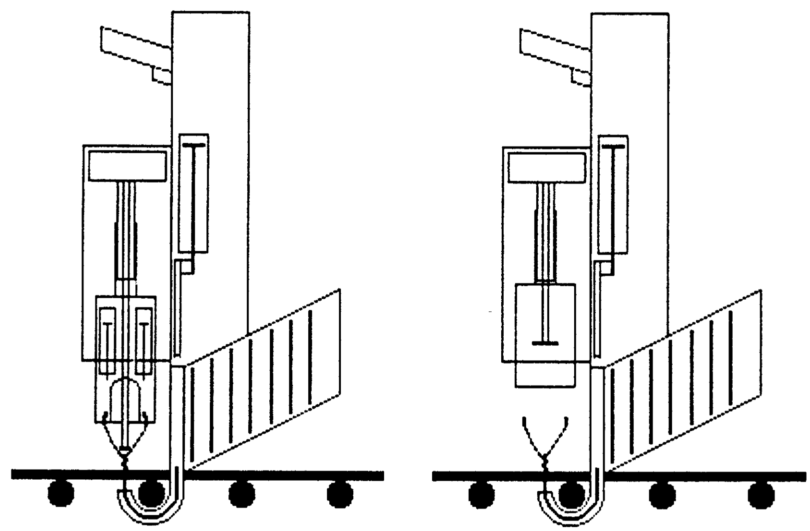
Figure 4 - 9
Step Seven - Release Tie

4.3.8 Step Eight - Full Retraction and Reset

Once the ends of the wire are released, the tensioning force causes the twisting and tying mechanism to fully retract. In addition, the twisting bar is also retracted. The twisting mechanism, the feeding mechanism, and the trigger mechanism are all reset. The device is now ready to begin the tying operation again.

Figure 4 - 10

Step Eight - Retraction and Reset



4.3.9 Step Nine - Remove Device

The final step is performed by the worker and is the reverse of step one. The worker simply removes the device from around the bars, and is ready to tie the next connection.

4.4 Detailed Design of the Wire Feeding and Loop Forming Mechanism

The detailed design of components of the tool follow in the next two sections. Design drawings are provided in Appendices 4 and 5 rather than in the text. Appendix 4 contains an assembly drawing of the cross section through the centerline of the tool, showing the spatial relationships between key components of the device. Appendix 5 contains various parts drawings. While reading the following sections, the reader may want to refer to the appendices and to the schematic diagrams provided previously in the chapter.

The wire feeding and loop forming mechanism is responsible for transferring a staple tie from its position in the queue to a position where the wire tensioning and twisting mechanism can secure the ends of the staple and complete the tying operation. The mechanism consists of a staple queue, a pneumatic actuating mechanism, and a pair of hooked loop forming members.

The staple queue contains the supply of staple ties. The queue is angled upward to prevent possible interference near the work surface. The strip of staples is correspondingly angled, as shown in Figure 4 - 2, with each successive staple offset slightly upward. The queue contains a spring mechanism which maintains the strip of staples in the forward most position in the queue. The spring mechanism is very much like the corresponding mechanism in a common stapler.

The pneumatically actuated feeding mechanism also acts very much like a common stapler, with the pneumatic actuator driving a formed member which forces the first staple in the queue to become dislodged from the stack. The pneumatic actuator will be single acting with a spring return and will have a stroke of 5.5 inches. The end of the formed member which contacts the staple is shaped to conform to the top of the staple tie. The other end connects to the actuator.

The formed member forces the staple tie downward to the hooked loop forming members which contain grooves to guide the ends of the tie. The loop forming members have a semi-circular shape with an inside diameter of 1.125 inches, to easily accept a size eight reinforcing bar. The ends of the tie are forced to bend around the bottom reinforcing bar. This step permanently deforms the wires, thus causing the wires to continue in a circular motion, with a curvature slightly less than that of the hooks' grooves, since the wire will rebound slightly when released.

4.5 Detailed Design of the Wire Tensioning and Twisting Mechanism

The wire tensioning and twisting mechanism, having been extended, contains wire receiving holes which are aligned with the grooves of the hooked loop forming members. The ends of the staple therefore continue in their circular trajectory into the receiving holes and into position for the wire holding mechanism.

The wire tensioning and twisting mechanism is cylindrical in shape, with an outside diameter of 2.5 inches. The majority of the cylinder is hollow, but the two inches at the end of the cylinder, which contains the wire holding mechanism, is solid to provide durability.

The wire holding mechanism is an integral part of the tensioning and twisting mechanism. It consists of the wire receiving holes, a single-acting, spring-returned pneumatic linear actuator, and two rods that are capable of axial motion. The pneumatic actuator, which has a 0.5 inch stroke, forces the 0.25 inch diameter rods through the two guide holes which are each aligned with the planes containing the two stages of the receiving holes. The end of the wire, having passed into the second stage of the receiving hole, is pinched between the rod and the bottom of the receiving hole, which acts as the wire holding anvil.

The twisting bar mechanism lies along the axis of and is connected to the tensioning and twisting mechanism cylinder. It consists of the twisting bar, an extension tube, and a single-acting, spring-returned, non-rotating pneumatic actuator with a 5.5 inch stroke. The twisting bar is attached to the end of the extension tube, which travels through and is guided by a hole through the end of the tensioning and twisting cylinder. The other end of the extension tube is secured to the actuator. The twisting bar moves with the actuator in the axial direction, but rotation is restrained since the actuator is non-rotating.

The solid end of the tensioning and twisting cylinder is machined to allow the end of the cylinder to fit over the reinforcing bars. Thus the cylinder can fully extend to place the end in contact with the hooked loop forming members. The upper end of the cylinder is fixed to a double-acting, double-ended, linear pneumatic actuator with a 5.5 inch stroke. The actuator extends and retracts the entire tensioning and twisting cylinder.

The upper end of the rod of the double-ended cylinder attaches to a toothed gear. The gear is free to translate axially as the actuator moves, but rotation is controlled by the cylindrical, co-axial, grooved gear which meshes with the toothed gear. The rotation is imparted to the grooved gear via a pneumatic rotary actuator and connected gearing. As the rotary actuator turns, a connected gear drives a chain which in turn drives the grooved gear.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of Work

This thesis has presented an innovative technology in concrete construction: semi-automated rebar tying. The major contribution of the project is a design for a hand held, pneumatically powered rebar tying tool.

Chapter 1 explained the motivation of the project and presented some of the potential impacts of the tool. A major impact of the tool is to relieve the worker from the grueling aspect of the tying task, bending over for long periods of time. The economics of rebar tying was discussed, concluding that the use of the tool could potentially result in cost savings to the concrete construction industry of three hundred million dollars per year. An additional motivation for the development of an automated rebar tying tool is the eventual integration of the tool into a fully automated system for fabrication of reinforcing steel.

Technological developments in concrete construction were characterized. A snapshot of the state-of-the-art in concrete construction was presented together with a history of key steps in the development of the technologies. Concrete technologies are shown to be shifting away from manual methods toward fully automated operations.

A detailed analysis of the task of rebar tying was performed, enabling a list of functional requirements for a rebar tying tool to be developed. A patent search was conducted, and eleven patented devices were studied in depth. The lack of success of the patented devices was explained as a failure to meet all functional requirements of the task.

The functional requirements led to the design of the improved tying tool. The operation of the tool was explained graphically with a series of schematic diagrams. Detailed designs of key components of the tool were presented and explained, with design drawings being included in Appendices 4 and 5.

Several key prototype components of the device have been fabricated and tested throughout the design process, to ensure that the components would work as expected. Two hooked loop forming members were fabricated to make sure that the wires could be pushed around the reinforcing bars. The solid end of the retractable wire tensioning and twisting cylinder was fabricated to insure that the trajectory of the ends of the wires would position them correctly within the wire receiving holes. Although the fabricated parts worked satisfactorily, the parts have not been assembled and the pneumatic actuators have not been incorporated into the prototype.

5.2 Suggestions for Further Work

The next step in the development of this tool is the construction of a complete prototype. The tool must be built to prove that the design satisfactorily performs the task. Once the prototype is operational, it should immediately be tested in the field. Valuable feedback can be gained from workers, which will undoubtedly lead to revisions in the design.

For total process automation to be achieved, rebar tying must be automated. There has been a substantial amount of research and development of the complimentary technologies for fully automated reinforcing operations. For example, automated rebar bending, fabrication, and placement have all been attempted and have achieved various degrees of success and use.

Once the design of the tool has been tested in the field and all "bugs" and inefficiencies have been corrected, work should be done to integrate the tool with some of the complimentary technologies for rebar fabrication.

Automated rebar tying is a key developing technology in the concrete construction industry. It is sure to change how concrete construction is performed. In addition to providing another step toward total automation in the evolution of concrete construction, automated rebar tying will allow complimentary technologies for reinforcing steel fabrication to be integrated into a fully automated system.

Appendix 1 - Portland Cement Varieties

Type I - normal

Type IA - normal, air-entrained

Type II - moderate sulfate resistance

Type IIA - moderate sulfate resistance, air-entrained

Type III - high early strength

Type IIIA - high early strength, air-entrained

Type IV - low heat of hydration

Type V - sulfate resistant

White portland cement

Colored portland cement

Oil well cement

Waterproofed cement

Plastic cements

Pipe cement

Block cement

Expansive cements

Epoxy cements

Masonry cement

Type IP - Pozzolanic cement

Type IPA - Pozzolanic cement, air entrained

High alumina

Type N - natural cement

Type NA - natural cement, air entrained

Type S - slag cement

Type SA - slag cement, air entrained

Appendix 2 - Admixtures

Air entraining Admixture - Increases Freeze/Thaw Durability

Water-Reducing Admixture - Reduce Required Mixing Water For a Given Slump

Retarding Admixture - Increases Setting Time

Accelerating Admixture - Decreases Setting Time

Pozzolans - Reduce Internal Temperature During Curing, Reduce Expansion Caused by Alkali Reactive Aggregates (ASR), Others

Silica Fume - Increased Strength, Decreased Chloride Permeability

Workability Agents - Provide Increased Workability

Superplasticizers - Increased Slump, Greatly Increased Workability, Increased Flowability and Pumpability, Decreased Required Mixing Water

Dampproofers - Reduce Permeability of Cured Concrete

Bonding Admixtures - Increase Bond Between Fresh Concrete and Existing Cured Concrete

Latex - Reduced Permeability, Increased Strength, Reduce Cracking

Coloring Admixtures - Create Colored Concrete

Corrosion Inhibiting Admixtures - Inhibit Corrosion of Reinforcing Steel

Appendix 3 - Patented Tying Devices

U.S. Patent 3,494,385 Tieing or Wire Twisting Tool
Inventor: Thomas J. Hanigan
Issued: February 10, 1970

U.S. Patent 3,590,885 Tool For Tying Wire
Inventor: James E. Ward
Issued: July 6, 1971

U.S. Patent 3,593,759 Wire Tying Tool
Inventor: Norman L. Wooge
Issued: July 20, 1971

U.S. Patent 4,177,842
Inventor: Gerald G. Dilley
Issued: December, 11, 1979

U.S. Patent 4,354,535 Hand-Held Automatic Wire Binding Tool
Inventors: Robert Y. Powell and Jeff A. Fisher
Issued: October 19, 1982

U.S. Patent 4,362,192 Wire Tying Power Tool
Inventors: Donn B. Furlong and Marvin M. May
Issued: December 7, 1982

U.S. Patent 4,653,548 Tool For Tying Crossing Elements
Inventor: Antonio Lucas Huerta
Issued: March 31, 1987

U.S. Patent 4,685,493 Reinforcing Bar Binding Device
Inventor: Sadao Yuguchi
Issued: August 11, 1987

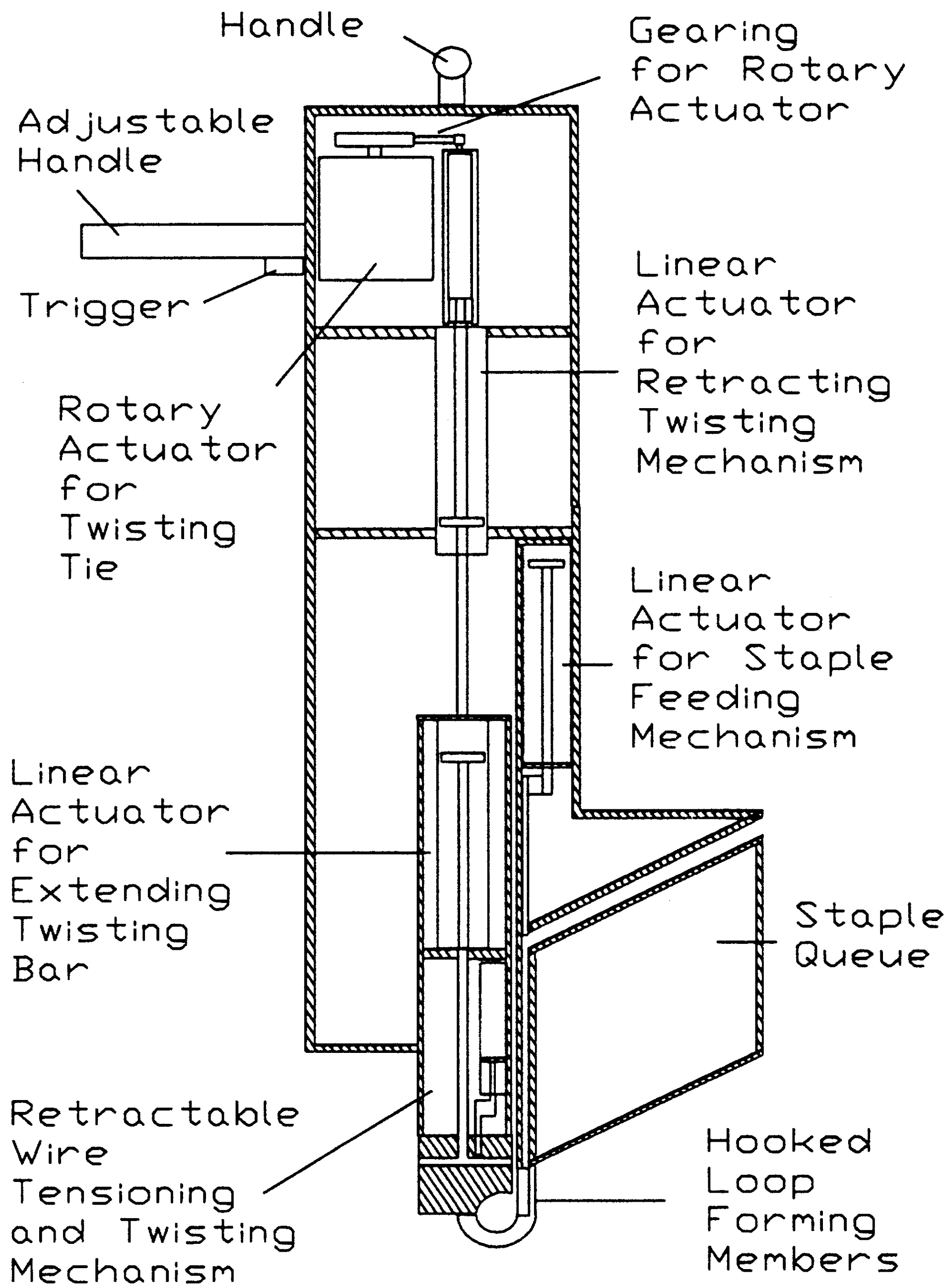
U.S.Patent 4,789,010 Apparatus For Manufacturing Reinforcements
Inventors: Wolfgang Reymann and Wilhelm Orth
Issued: December 6, 1988

U.S. Patent 4,834,148 Reinforcement Binding Machine
Inventors: Hiroshi Muguruma, Hiroshi Toyoda, and Takayasu Sawano
Issued: May 30, 1989

U.S. Patent 4,865,087 Wire Tying Mechanism
Inventor: Robert E. Geiger
Issued: September 12, 1989

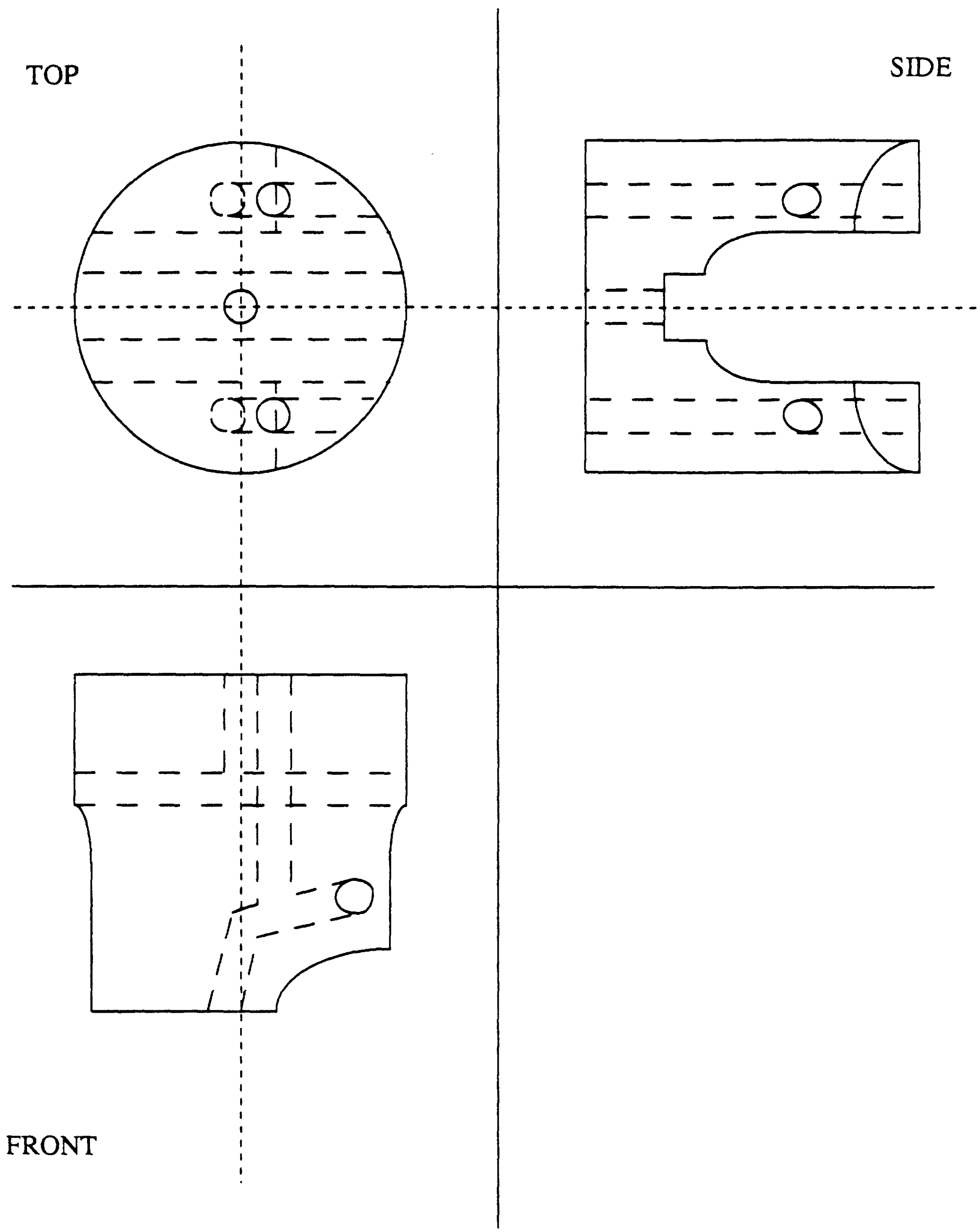
Appendix 4

Assembly Drawing



APPENDIX 5
END OF TENSIONING AND TWISTING CYLINDER

THREE ORTHOGRAPHIC VIEWS

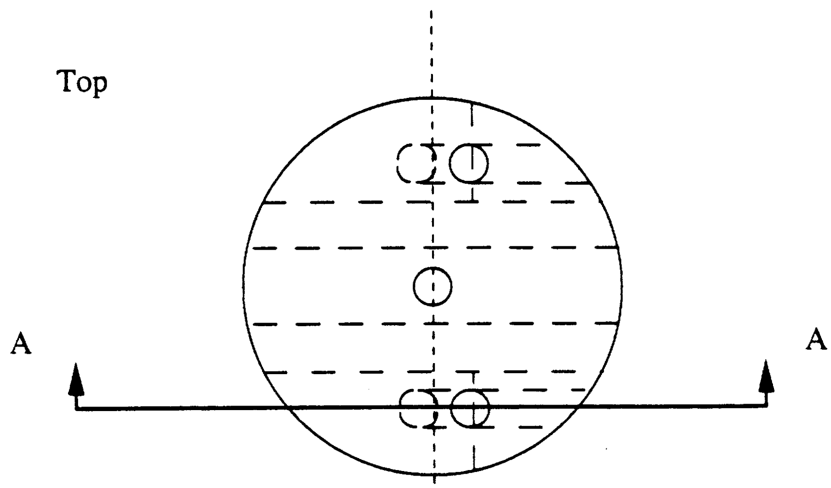


APPENDIX 5

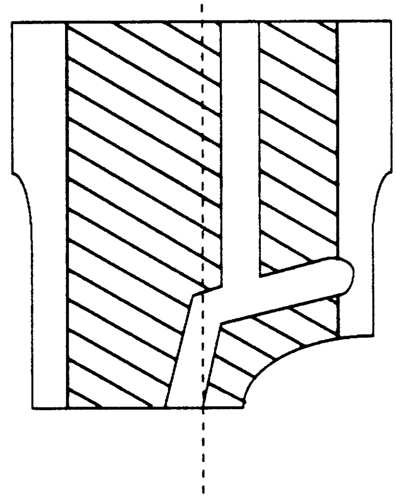
END OF TENSIONING AND TWISTING CYLINDER

SECTION VIEW OF WIRE RECEIVING HOLES

Top



Section A-A



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