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Guidelines for Circular Rebar Cage Assembly with U-bolt Connectors

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October 2023

Acknowledgments

This guideline document is the result of a research project initiated through ASCE Construction Institute and funded by Charles Pankow Foundation (Research Grant Agreement #01-20) and several industry partners listed in spelling alphabetical order: ASCE Construction Institute, Association of Drilled Shaft Contractors, Association of Foundation Drilling, Concrete Reinforcing Steel Institute, Harris Rebar/Nucor, Keller Companies, Kiewit Corporation, Parsons Corporation, P.J.'s Rebar, Siefert Associates LLC, and Williams Form Engineering. The financial support is gratefully acknowledged. The authors would also like to especially thank Mr. Vince Siefert, President of Siefert Associates LLC and chair of the industry steering committee, for his unwavering support and contribution to this research project. The authors would like to extend their sincere appreciation to members of the industry steering committee, Angie Hunter, Anne Ellis, Brett Lord, Brian Ruegge, Jeff Veilleux, Justin Ramer, Katerina Lachinova, Lyle Sieg, Mark Bennier, Mark Perniconi, Peter Speier, Ray Fassett, and Tanner Blackburn, for their invaluable contributions and unwavering support throughout the research project.

Table of Contents

1 Introduction

1.1 Background

Prefabricated rebar cages are widely used in above-ground and below-ground reinforced concrete construction. Examples include construction of bridge piers, columns, cast-in-drilled-hole piles, and slurry wall foundations. These temporary structures usually consist of longitudinal and transverse rebars connected by tie wires. Despite the increasing demand for prefabricated rebar cages in the construction industry, there are currently limited guidelines for design, fabrication, and site handling of the rebar cages. The lack of guidance leads to increased vulnerability and risk of failure of these structures, resulting in safety hazards, liability, project delays, and added construction costs.

State of the practice for rebar cage construction involves tying the longitudinal and transverse reinforcement bars using black annealed steel tie-wire connections. However, experimental-analytical investigations conducted by Builes-Mejia et al. ([1], [2]) showed that the failure of rebar cages is governed by the tie-wire connection failure, rendering the tie-wires as the "weak links" in the rebar cage structural system. As a result, alternative methods for connecting the rebars have been explored. This document introduces the application of mechanical U-bolt connectors for cross-bar connection at specified intervals to improve structural behavior of the rebar cages ([3]–[5]). This guideline is developed based on a comprehensive experimental-analytical research campaign to study the behavior of U-bolt connectors, as is briefly summarized below.

Through a series of experimental tests, first, the force-deformation response of U-bolt connectors has been determined for cross-rebar connection [6]. U-bolt connectors are found to provide significantly higher strength and stiffness compared to tie-wire connections. In a subsequent study, a total of 26 full-scale experimental tests were performed on five different circular rebar cages with tie-wire and/or reinforced with U-bolt connectors to investigate the behavior of rebar cages under common site handling conditions, such as lifting and tilting [6]. The performed tests showed that the cages with mechanical connectors and without internal stiffening elements remained stable under all loading conditions that mimic various site handling processes. The tests were followed by a numerical investigation, in which detailed finite element (FE) models of rebar cages were developed, calibrated, and validated using experimental results. The numerical models were able to accurately predict the response behavior of rebar cages reinforced with U-bolt connectors, as well as traditional tie-wired rebar cages with internal stiffening elements. However, development of properties for rebar cages with internal stiffening elements was outside the scope of this research phase. Therefore, the information provided in this guideline only applies to rebar cages that are lifted without internal stiffening elements.

Through parametric studies and dimensional analysis, analytical models were developed to characterize the stiffness properties of a rebar cage as a function of its physical properties. The derived stiffness properties can then be used to develop a simplified beam model for rebar cages that do not have internal stiffening elements. This will enable engineers to analyze the deflection of rebar cages under site loading conditions without relying on complex and expensive numerical models.

1.2 Intended Audience

The information contained in this guideline is intended to assist those involved in the design, construction, and fabrication of rebar cages, including but not limited to rebar cage fabricators and practitioners, contractors, construction engineers, design engineers, and academics.

1.3 Anatomy of a Rebar Cage

Rebar cages are usually fabricated by ironworkers using steel reinforcing bars in sizes ranging from #4 to #18. The reinforcement in these cages often consists of longitudinal and transverse rebars connected by tie wires or, as will be offered in this guideline, by mechanical U-bolt connectors. The tying process adheres to design specifications and is executed using standard methods as prescribed by the Concrete Reinforcing Steel Institute (CRSI) [7]. Pick-up bars are identified as the longitudinal bars used to facilitate the lifting and movement of the cage from a horizontal to a vertical position. Fully tied hoops are also specified by some agencies and often used throughout the length of the cage as fabrication templates and/or to maintain the proper spacing and orientation of the longitudinal bars.

Throughout this guideline, internal stiffening elements (ISEs) are referred to as those items used to ensure the stability of the cage and/or to prevent section deformation during lifting. The types of ISEs that provide the listed functions are not the same and may or may not be combined into one unit. At a minimum, ISEs that provide a diagonal load path along the length of the cage are used as industry standard practice to ensure stability during fabrication and transportation (e.g., while the cage remains in the horizontal condition). Z-bars are an example of this type of ISE. For below-grade cages, these elements often need to be removed on site after the cage has been lifted to the vertical condition, prior to lowering into the ground to create clearance for the concrete placement and/or to meet seismic detailing requirements. For above-grade cages, the diagonal components are preferably able to remain in place to provide a load path for stability when the cage is in the vertical position.

Other types of ISEs include those which locally reinforce the cage's round cross-section. Inner ring systems and/or wagon wheels are sometimes employed as part of a complete ISE unit or as individual rings placed at specified intervals and/or at lifting points along the cage. The need for these localized stiffening rings should be determined by a qualified engineer, based on the anticipated crushing loads during fabrication and rigging loads (perpendicular to the cage) that will take place during lifting operations.

Fig. 1 and Fig. 2 show schematics of rebar cage components and examples of internal stiffening elements. See Appendix 1 for definitions and further clarification.

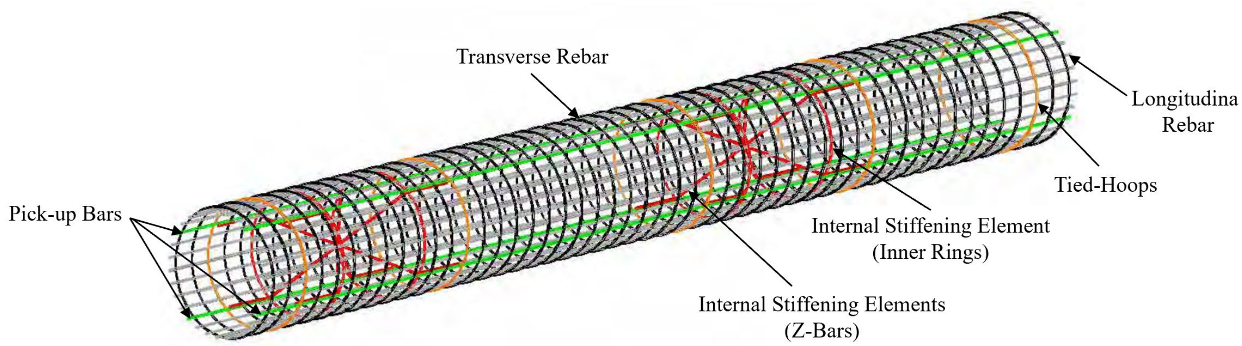


Fig. 1. Rebar cage components.

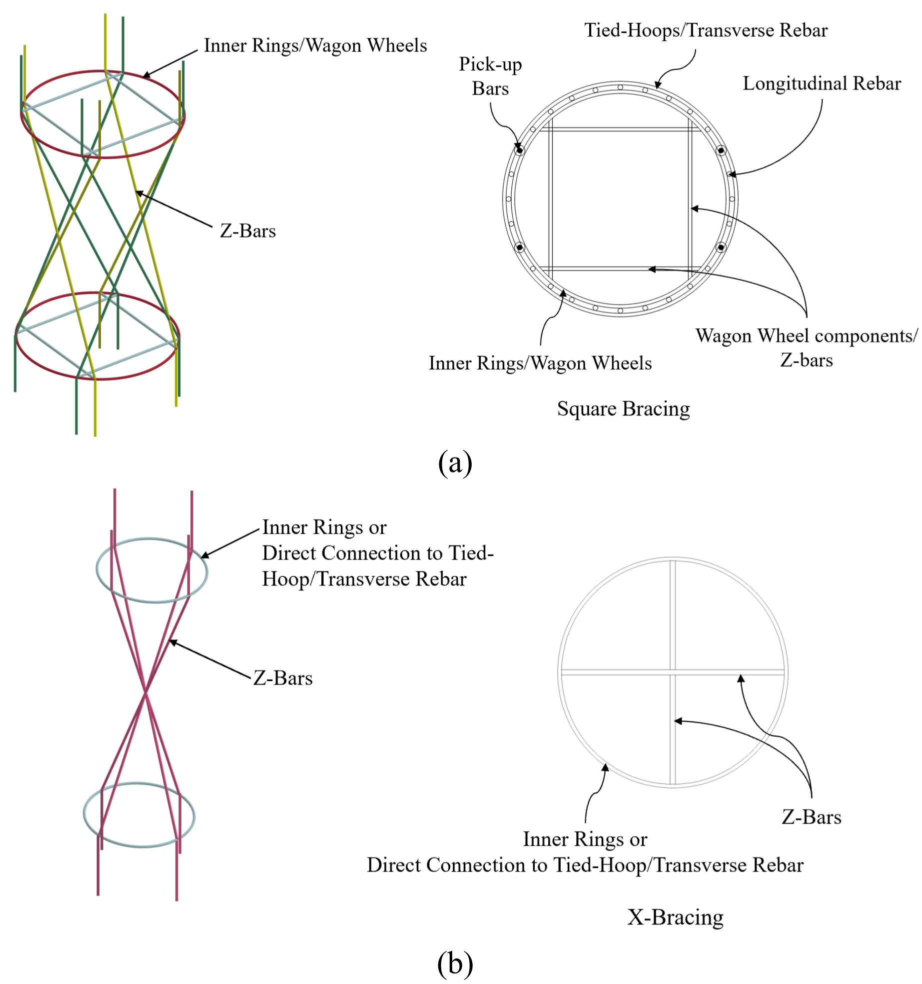


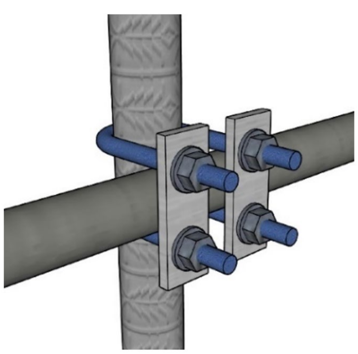
Fig. 2. Schematics of different types of internal stiffening systems: (a) Square bracing, (b) X-bracing.

1.4 Objectives of the Guideline

In state of the practice, internal stiffening elements are commonly used to enhance the stiffness and stability of tie-wired rebar cages. However, as described in section 1.3, z-bracing components of the internal stiffening elements must often be removed after the cage has been lifted and rotated to the vertical condition. The process is usually cumbersome and requires careful planning to avoid injuries to workers and failure of the rebar cage. Mechanical U-bolt connectors can offer a viable alternative solution to eliminate the need for z-bracing components of internal stiffening elements during the lifting and handling of cages.

Analytical results from this project also indicate that U-bolt connectors could eliminate the need for z-bracing components of internal stiffening elements for fabrication and transportation, and possibly for the vertical condition of above-grade cages as well. However, testing for those conditions was outside the scope of this research phase. It will be necessary to perform detailed analysis and testing in a future research phase to confirm that these preliminary observations are safe to employ in practice.

This guideline provides a systematic design approach for fabrication of rebar cages with U-bolt connectors to ensure the stability and safety of prefabricated rebar cages during the lifting process based on the outcomes of the studies mentioned earlier in the guideline. The purpose of this guideline is not to contravene or challenge previous guidelines and practices, but to provide an alternative solution with a better understanding of the behavior of rebar cages. By providing a set of recommendations, this guideline aims to promote the adoption of U-bolt connectors as a viable solution to improve the overall safety of rebar cages during the lifting stage of construction.



(a)

(b)

Fig. 3. (a) Schematic view of U-bolt connector, (b) an assembled U-bolt connection on a cross-bar connection in a rebar cage.

2 State of the Practice Assembly Recommendations for Tie-Wired Rebar Cages

The State of Practice summary below is based on Section 52 of the Caltrans Standard Specifications [8]. Note that the state of practice may vary outside California, as construction practices, regulations, and industry standards can differ from state to state or country to country. It is important to emphasize that this guideline is not intended to impose or invoke the existing requirements or practices.

The Caltrans specification provides the following recommendations for the assembly of circular rebar cages with 4 feet or larger diameter:

1. No. 15 gauge soft annealed black steel wires (or stronger) with a minimum ultimate strength of $F_u = 40$ ksi should be used for tying rebars.
2. At least four longitudinal (or vertical) rebars equally spaced around the circumference (also identified as pick-up bars) shall be tied at every intersection with at least double-tie wire connections. The strength of these connections shall be adequate for picking up the cage.
3. Tied-hoops shall be at a maximum of 8 feet increments. Tied-hoops shall be tied at every intersection with longitudinal rebars with at least wrap-and-saddle tie wire connections.
4. At least 20% of the remaining intersections (every fifth) of longitudinal and transverse rebar shall be tied with single-tie wire connections. The connections shall be staggered from adjacent connections.
5. Internal stiffening elements (Z-bar bracing) shall be provided to avoid failure of the cage during assembly, transportation, and installation.

The cages that were tested for this guideline were initially fabricated based on the Caltrans specification. The Tied Hoop spacing was then optimized based on the testing results. Minimum assembly guidelines for circular rebar cages with U-bolt connectors are provided in Section 4 of this document.

3 U-bolt Connector Material Properties and Installation

The recommended material for U-bolts is ASTM A29/A108 Grade 1541 steel with the yield stress of 105 ksi and tensile strength of 120 ksi, and for plates is A36 steel. The distance between U-bolt's legs should be consistent with the diameter of the longitudinal rebar. Fig. 4 depicts the dimensions of the mechanical U-bolt connector, including the U-bolt and plate, designed for #11 longitudinal rebar.

U-bolts can be used to connect longitudinal rebar to either the transverse rebar, with the U-bolt legs positioned on the outer face of the cage, or the inner rings, with the U-bolt legs positioned on the inner side of the cage (see Fig. 5). Both methods are acceptable, each with its own advantages and drawbacks. The first method is easier for assembling the U-bolts as an ironworker outside the cage can tighten the nuts; but, it involves U-bolts intruding into the concrete cover. The second method requires an ironworker to reach inside the cage to tighten the nuts, making assembly more challenging, but with limited intrusion on the concrete cover. For safety, allowing workers to fully enter the cage should be avoided. If this is necessary, analysis of cage stability during fabrication should be confirmed by a qualified engineer. It is also worth mentioning that based on our observation, a worker can assemble at least 13 U-bolts per hour.

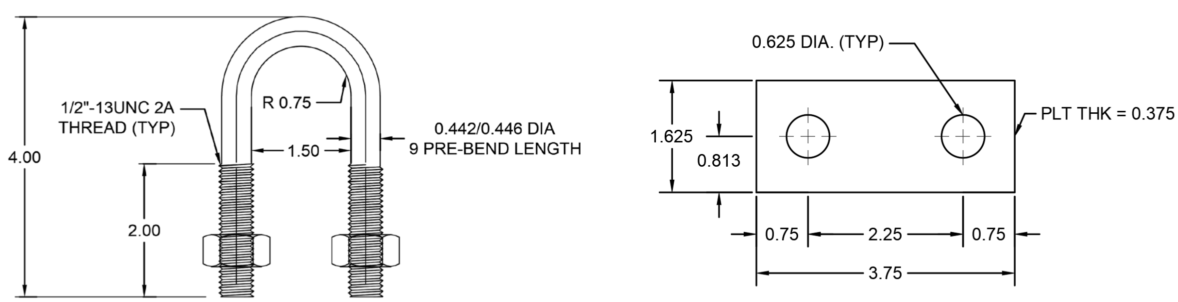
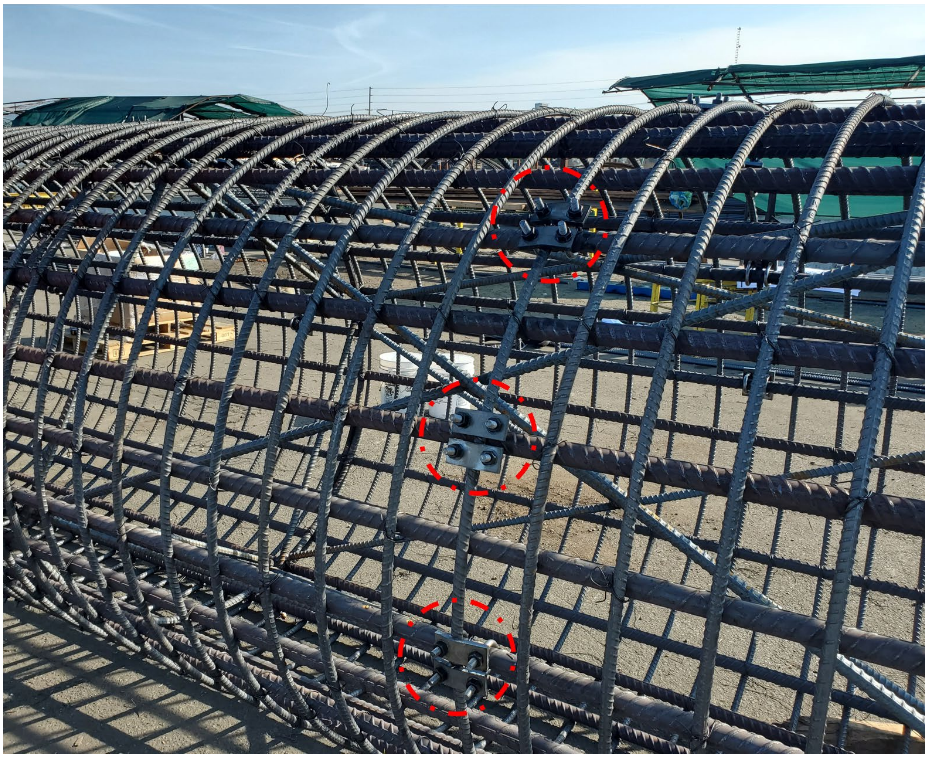
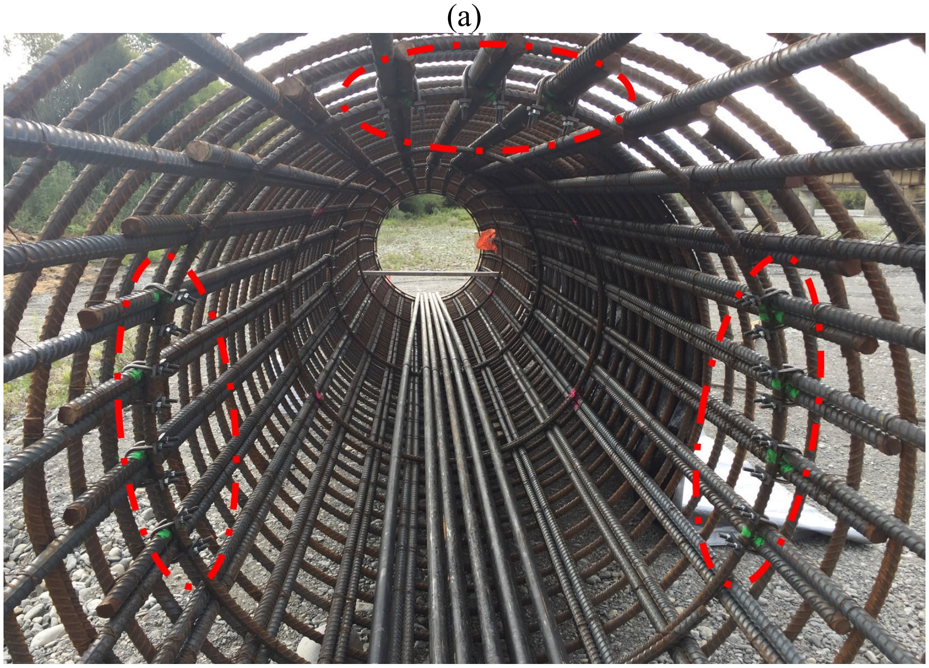


Fig. 4. U-bolt and plate details (dimensions are in inches).



(a)



(b)

Fig. 5. (a) U-bolt connectors used to connect longitudinal rebars to transverse rebars, (b) U-bolt connectors used to connect longitudinal rebars to inner rings.

4 Assembly Guidelines for Circular Rebar Cage with U-bolt Connectors

To assemble circular rebar cages with U-bolt connectors and without internal stiffening elements, the following guidelines are recommended. It should be noted that the term "without internal stiffening elements" refers to the removal of internal diagonal rebars (Z-bars) along the length of the rebar cage. Inner rings or wagon wheels used for fabrication purposes to prevent ovalization and in-plane distortion of the rebar cage shall not be removed. Additionally, note that these guidelines are only intended to apply to rebar cages with diameter of 4 feet and larger at this time. Cages of smaller diameters may be explored in a future research phase.

1. Tied-hoops are recommended to be placed at intervals up to 10 feet starting from the top of the rebar cage and fastened to all pick-up bars with U-bolt connectors (see Fig. 6). The remaining intersections of tied-hoops and longitudinal rebar should be tied with at least wrap-and-saddle tie-wire connections.
2. At each tied-hoop location, at least 14% of the longitudinal rebars, but not less than the values shown in Table 1, are recommended to be fastened to the tied-hoop using U-bolt connectors. This includes the U-bolts on the pick-up bars. The number of U-bolt connectors on each tied hoop should be an even number and assembled in a symmetric configuration. Table 1 summarizes the number of U-bolt connectors per tied-hoop in relation to the number of longitudinal rebars.

Table 1. Minimum number of U-bolts per tied-hoop

Number of longitudinal rebar	Minimum number of U-bolts per tied-hoop
≤ 28	4
29-42	6
43-56	8

3. Pick-up locations are the most influential factor in minimizing cage loads and deflections. Pick-up locations should be optimized so that overhang spans counteract the gravity loads from pick-up spans. The lift point configurations shown in Fig. 7 and Fig. 8 suggests pick-up points for two-point and three-point lifts. These suggestions exclude the effects of concentrated loads along the cage, including but not limited to mechanical couplers and load cells. Note that three-point lifts typically require using a rolling hitch, which must be analyzed by a qualified

engineer for continuity considering the stiffness properties of the cage. **Rolling hitches <u>cannot</u> be analyzed by simply modeling each pick-up point as a support.**

4. The maximum distance between the pick-up points, i.e., pick-up span, is recommended not to exceed 32 feet.
5. The rigging angle of pick-up cables is recommended not to be less than 65˚ from a horizontal plane. Note that rigging angles result in axial compression in the cage during lifting and should be analyzed by a qualified engineer.
6. The maximum overhang length is suggested to be less than half of the pick-up span unless other engineering provisions are considered.
7. The pick-up points are recommended to be at the intersection of tied-hoops and pick-up bars connected with mechanical connectors, as shown in Fig. 9. Note that sling cables must be protected at sharp corners with softeners.
8. Until further testing and analysis are performed, internal stiffening elements should be present in the cages to ensure stability during fabrication and transportation, per current industry practice. However, when U-bolts are employed per this guideline, the diagonal Z-bar components of the ISE's may be removed while the cage is on the ground in the horizontal condition, prior to lifting to vertical.
9. U-bolt shall be tightened properly and consistently until the plates bend for approximately 5 degrees to ensure proper connection strength, as demonstrated in Fig. 10.

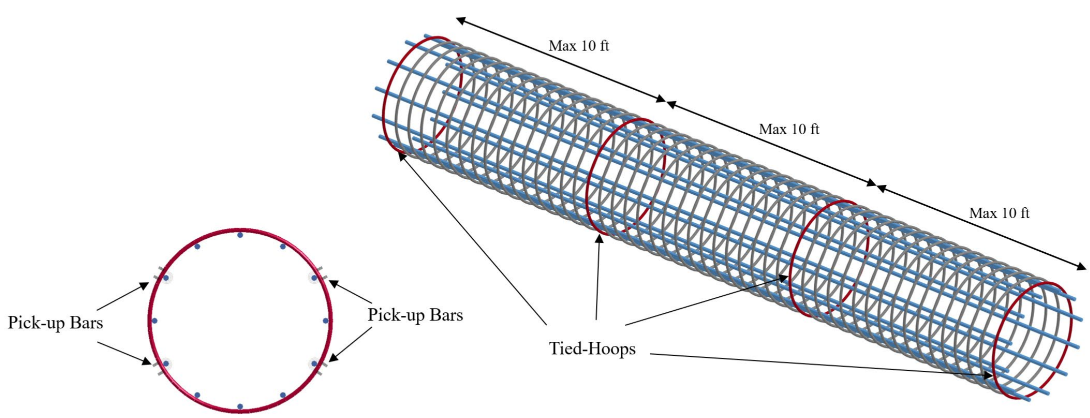


Fig. 6. Schematic of tied-hoops and pick-up bars in a rebar cage.

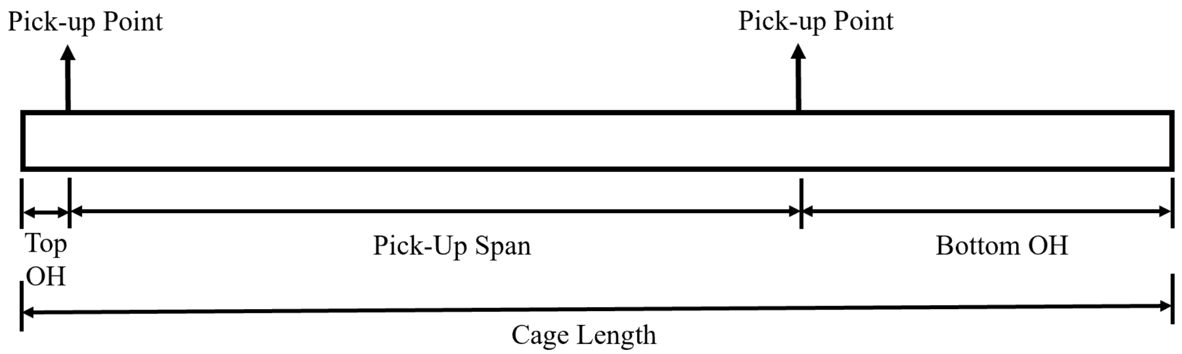


Fig. 7. Two Point Lift: Top OH (TBD based on field requirements, but typically 1' to 2'), Bottom OH = (Cage Length - Top OH)/3. OH stands for Overhang.

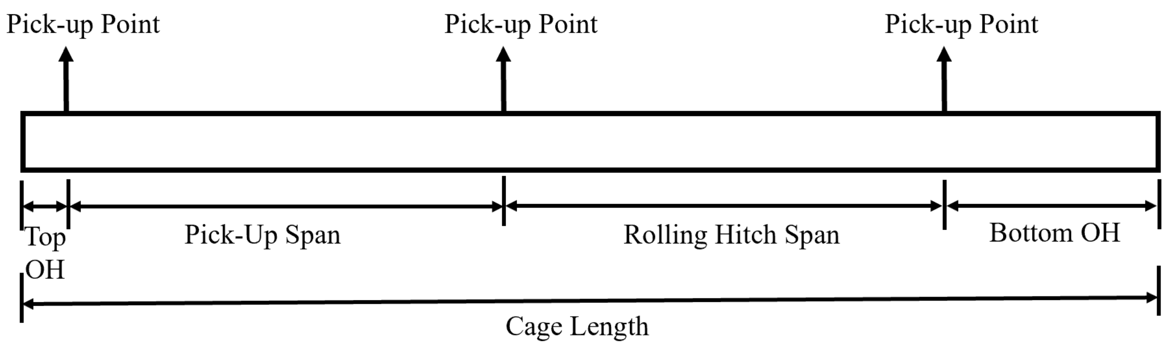


*Fig. 8. Three Point Lift: Top OH (TBD based on field requirements, but typically 1' to 2'), Bottom OH = (Cage Length - Top OH)/5, Rolling Hitch span = Bottom OH*2. OH stands for Overhang.*

Fig. 9. Pick-up points at the intersection of tied-hoops and pick-up bars

Fig. 10. Bending of the U-bolt connector plates in a tight-fit connection.

5 Rebar Cage Stiffness Parameters

Prior to employing the parameters in this section, it is important to note that cages without internal stiffening elements will experience larger deflections than cages with internal stiffening elements, as confirmed through testing and industry experience. Therefore, to maintain deflection limits as may be required for other pre-installed components (such as prevention of steel Crosshole Sonic Logging tube breakage), it may be necessary to employ a greater number of pick-up points than those currently used throughout the industry. Future research phases may evaluate the combined effects of U-bolts and internal stiffening elements with the goal of achieving an overall increased cage stiffness.

Equations (5-1) and (5-2) may be used to determine the "effective moment of inertia" and "effective shear area" of circular rebar cages without internal stiffening elements with and without U-bolt connectors (see notes below). By employing these stiffness parameters, a simplified equivalent beam model of a rebar cage can be created to estimate its deflection. This beam model must be run in a finite element analysis software, including nonlinear geometric effects.

$$I = n \cdot D_r^4 \cdot (0.06 + 0.04 \cdot C^{0.79}) \quad (5\text{-}1)$$

$$A_s = \rho^{1.54} \cdot \rho_s^{0.04} \cdot \frac{(0.25 + 0.43 \cdot C)}{100} \cdot D_c^2 \quad (5\text{-}2)$$

in which,

I = effective moment of inertia of rebar cage, in^4

n = number of longitudinal rebars

D_r = diameter of a longitudinal rebar, in

C = ratio of the number of longitudinal rebars fastened to tied-hoop using U-bolt connectors vs. the total number of longitudinal rebars

A_s = effective shear area of rebar cage, in^2

ρ = longitudinal steel ratio, i.e., ratio of the longitudinal reinforcement area to the total cross-section area of the rebar cage calculated as $\rho = \frac{n \cdot A_r}{\pi \cdot \frac{(D_c)^2}{4}}$

ρ_s = transverse steel ratio, i.e., ratio of the volume of transverse reinforcement to the total volume of the cage, calculated as $\rho_s = \frac{\pi \cdot (D_c) \cdot A_t}{\pi \cdot \frac{(D_c)^2}{4} \cdot s}$

of core confined by the transverse reinforcement, measured out-to-out of transverse reinforcement

D_c = diameter of the rebar cage measured to outside diameter of transverse reinforcement, in

A_r = cross-section area of the longitudinal rebar, in^2

A_t = cross-section area of the transverse rebar, in^2

s = center-to-center spacing of transverse rebars, in

Note that when $C = 0$, the above equations can be utilized to estimate the stiffness parameters of a tie-wired rebar cage without U-bolt connectors and internal stiffening elements. However, it is essential to acknowledge that a tie-wired rebar cage without U-bolt connectors and internal stiffening elements is deemed unsafe, with a risk of failure. Therefore, it is not recommended.

It is acknowledged that cages with internal stiffening elements and without mechanical connectors represent the current industry standard. However, it is important to note that the equations provided in this section are not suitable for calculating section properties of cages with internal stiffening elements. Further research into applicable equations has been recommended by stakeholders, and development is anticipated with industry participation.

6 Design Limits and Procedure

6.1 Deflection limit

According to the experimental tests described in [6], rebar cages reinforced with U-bolt connectors and without internal stiffening elements were able to withstand over 13% of their pick-up span deflection without experiencing any damage or failure. Based on both experimental and analytical investigations, the following deflection limit is suggested for the horizontal lifting of circular rebar cages reinforced with U-bolt connectors and without internal stiffening elements:

For rebar cages with rebar #10 and above, the maximum calculated deflection of the rebar cage is recommended not to exceed 10% of the corresponding pick-up span.

$$\Delta < 0.10 \cdot l \quad (6\text{-}1)$$

where l = pick up span.

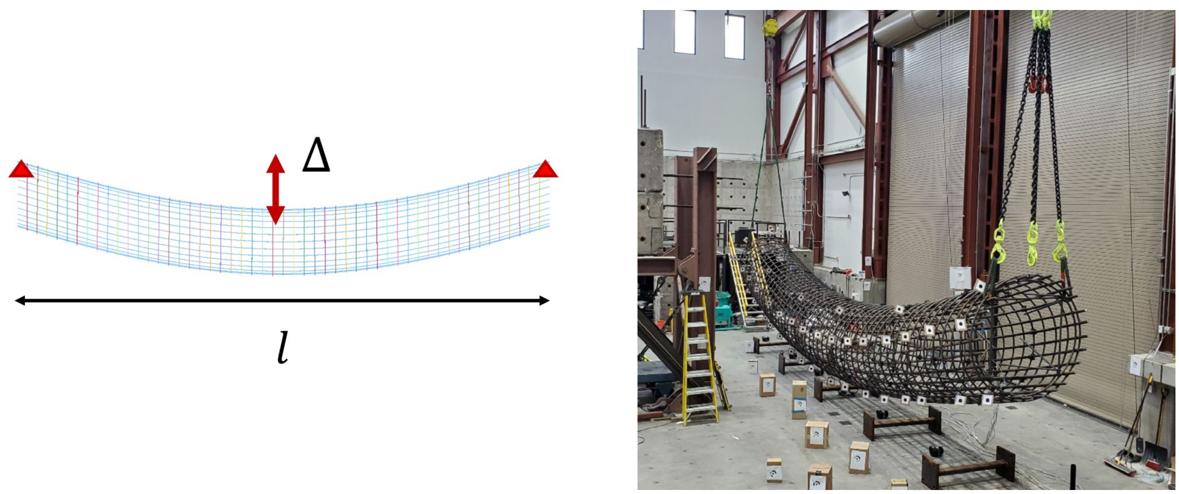


Fig. 11. Rebar cage deflection.

Note that Crosshole Sonic Logging (CSL) tubes are common components in below-ground rebar cages. The deflection criteria for site-specific CSL tubes may be different from the recommended cage deflection. Additionally, use of internal stiffening elements may require a stricter deflection limit to avoid failing those elements. Practicing engineers are advised to consider deflection limits accordingly.

6.2 Design Procedure

The design procedure for rebar cage with U-bolt connectors and without internal stiffening elements, including the U-bolt layout and pick-up locations, is proposed as follows. The steps of this procedure are summarized in the flowchart depicted in Fig. 13.

Step 1: Specify the properties of the rebar cage, including the weight of the rebar cage (W), number of longitudinal rebar (n), diameter of rebar cage (D_c), diameter of longitudinal rebar (D_r), longitudinal steel ratio (ρ), and transverse steel ratio (ρ_s), based on the structural design of the rebar cage.

Step 2: Determine the U-bolt layout and pick-up points based on the recommendations provided in Section 4.

Step 3: Calculate the effective moment of inertia (I) and effective shear area (A_s) using equations (5-1) and (5-2). The bending stiffness (EI) and shear stiffness (GA_s) of the rebar cage cross-section can then be assumed as $E = 29 \times 10^3$ ksi and $G = 11.2 \times 10^3$ ksi.

Step 4: Model the cage deflection using a simplified equivalent beam. For this purpose, use a Timoshenko beam with stiffness parameters calculated in Step 3 (EI and GA_s), accounting for nonlinear geometric (i.e., large displacement) effects. For two-point lifts with vertical rigging, pick-up points may be modeled as simple supports, with one designated as hinge support and the other designated as roller support[1]. The weight of the rebar cage must be defined as a uniformly

[1] Note that:

- For cages with inclined rigging, the rigging must also be modeled to account for the axial loading effects on the cage.
- For cages with more than two pick-up points:
  - These cages cannot be modeled with more than two supports, as the cage stiffness/rigging tension interaction has a significant effect on the resulting cage loads and deflection.
  - All rolling hitch rigging lines must be modeled and adjusted to reach equilibrium (equal tensions on each line).
  - Cages must be analyzed in both the horizontal condition and the inclined condition, as the rolling hitch effects often create loading scenarios during incline that control the cage stresses and displacements.
- When inclined rigging is used, confirm adequacy of the cage for anticipated axial loads based on engineering principles. Further research is warranted to evaluate axial loading effects and provide guidance on an appropriate evaluation methodology.

distributed load along the length of the simplified equivalent beam. Solve the simplified equivalent beam model of the rebar cage using structural analysis software (e.g., SAP2000).

Step 5: The deflection of the rebar cage should meet the deflection limit criterion. If not, change the pick-up point locations and repeat the procedure from Step 2 with new pick-up points until the deflection limit is met. Otherwise, try increasing the number of U-bolts, and again repeating the procedure from Step 2. If the deflection criterion is still not met, then more than two pick-up points will be required.

Step 6: When the rebar cage is suspended vertically, the cage weight will be transferred according to the load path shown in Fig. 12.

- Distributed load is transferred to pick-up bars via strength of the hoop. This guideline applies to the use of 4 pick-up bars, and hoops are typically adequate by observation for that configuration. When two pick-up bars are used (outside the scope of this guideline), the hoop strength and stiffness must be verified as adequate for this load transfer.
- The load is then transferred from hoops to pick-up bars via friction at tie wires and/or in this guideline, the U-bolt connectors where applicable.
- The load in the pick-up bars is then transferred to the rigging (via friction at choker and/or through rigging safety stops). For the purposes of this guideline, U-bolts at the pick-up hoop at the head of the cage will be checked for transferring the entire load (ignoring tie wires, rigging friction, and/or other mechanical safety stops).

The minimum number of U-bolt connectors at the pick-up hoop for vertical lifting should be checked as follows. This verification ensures that the U-bolts remain within their elastic range of their strength capacity (for further details, refer to [5] for U-bolt response and behavior).

$$n' \geq \frac{w}{5}$$

in which,

w = weight of the rebar cage (kip)

n' = number of U-bolt connectors at vertical lifting pick-up hoop

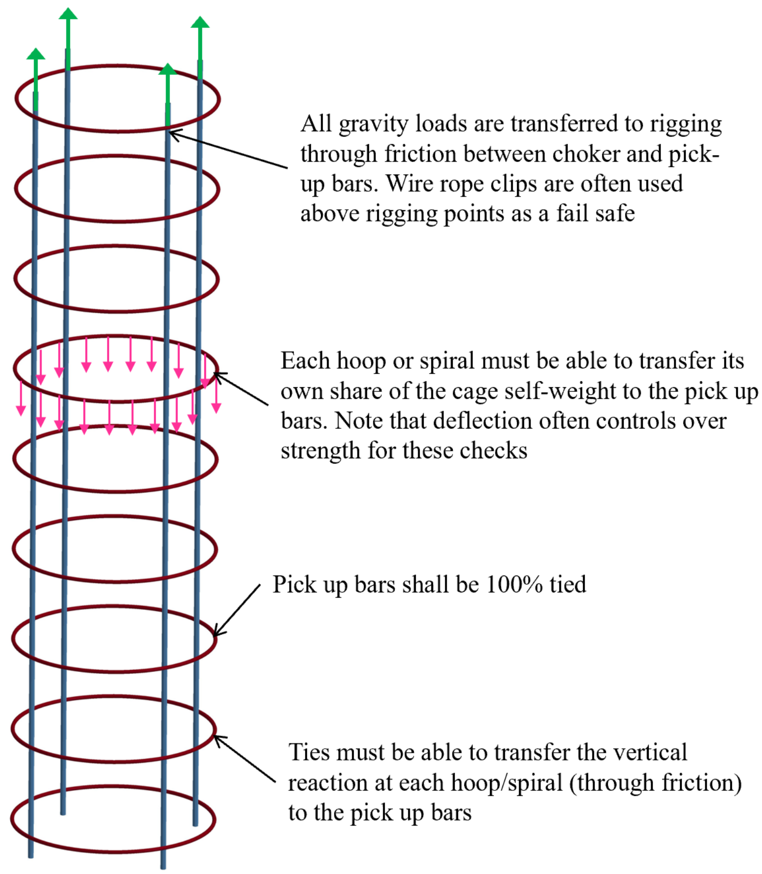


Fig. 12. Load path for vertical condition (four pick-up bars shown, two pick-up bars follow similar load path)

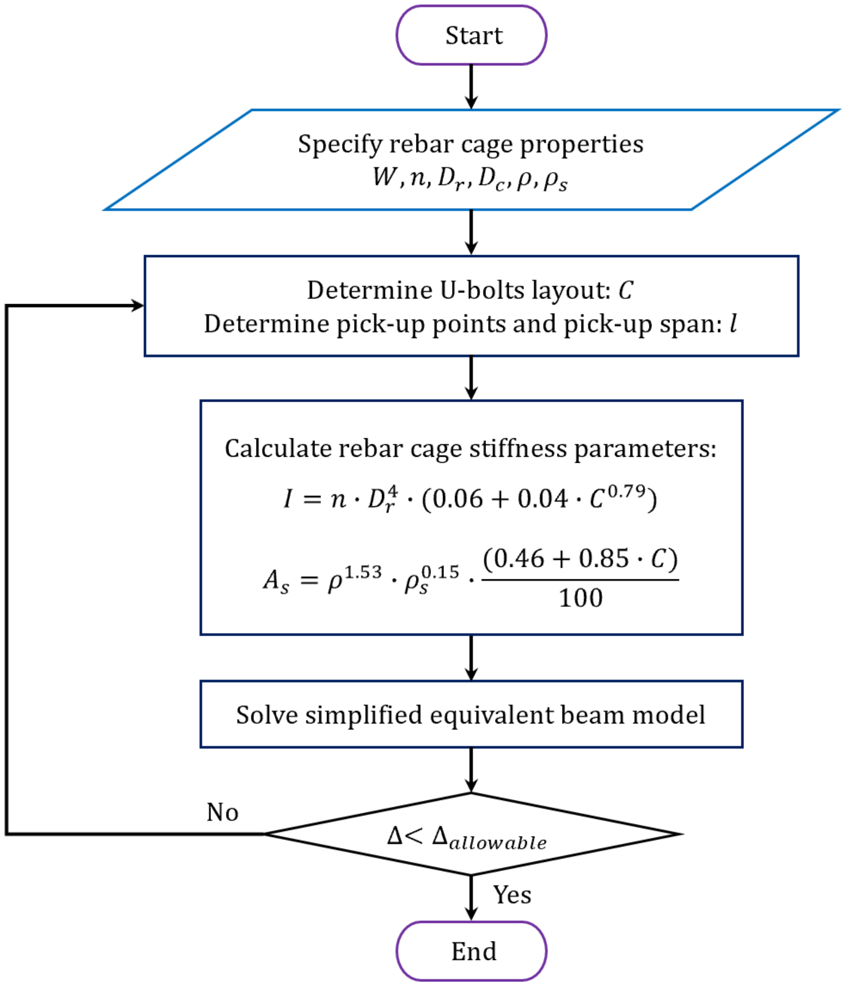


Fig. 13. Design procedure flowchart to determine layout of U-bolts and pick-up locations.

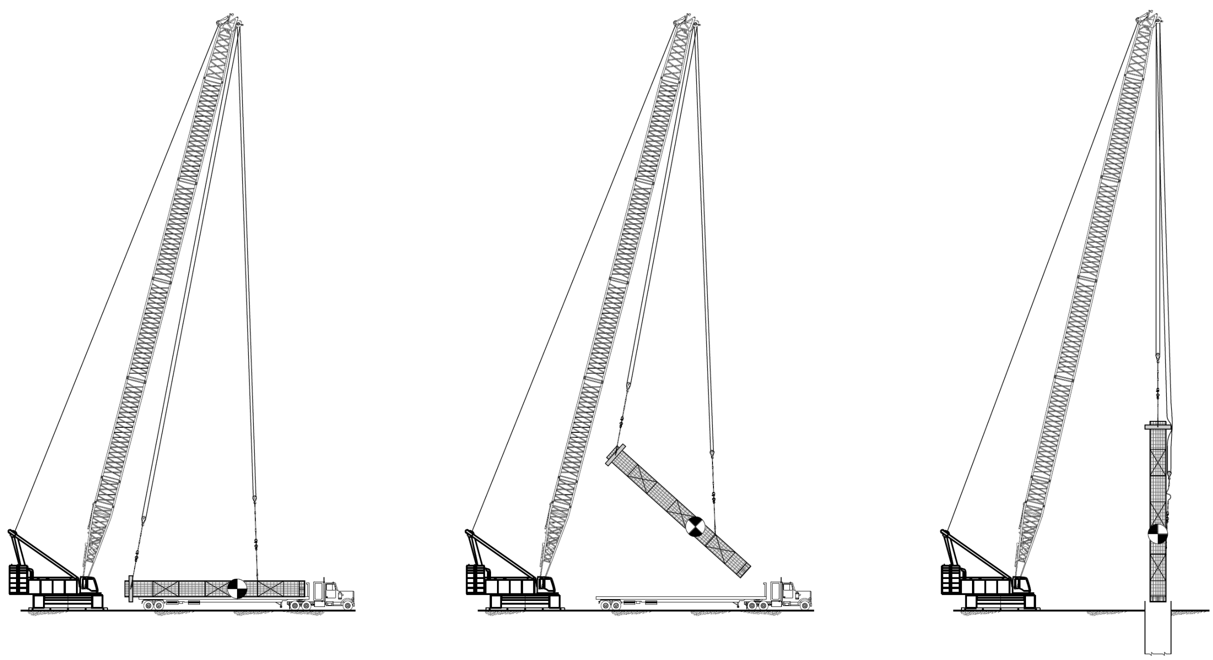
7 Upending Procedure and Vertical Placement

Rebar cages can be upended to a vertical configuration through different rigging arrangements and procedures. The research performed in this project mainly focused on the analysis of a two-point pick. Many rebar cages require multiple pick-up points to maintain acceptable deflection and stability. For large rebar cages, typically those with a length of 55 ft or more, three or more pickup points will be required, and it is recommended that a qualified engineer perform engineering analysis for the rigging process to ensure safety and proper execution. Fig. 14 shows some examples of lifting process for rebar cages with two, three, four, five, and seven pick-up points. The following is a general outline of the step-by-step process involved in lifting a rebar cage from a horizontal position and upending it to a vertical configuration with a single crane, provided for information only.

1. Assess the site and ensure that the crane has enough space to maneuver and lift the rebar cage safely. Consider the length of the cage and ensure that the area allows for proper placement.
2. Position the crane in a location that provides adequate clearance for the full length of the cage to be aligned directly below and parallel to the boom length, and has the required reach and capacity for upending without contacting the crane boom. Consider the stability of the ground and any potential obstacles that may impede the lifting operation.
3. Connect the rigging equipment by securely attaching the lifting slings to the cage at designated pick-up points.
4. Perform pre-lift checks, including connections and rigging equipment.
5. Initiate the lift by applying tension to the main and auxiliary load lines connected to the lifting slings. Lift the cage slowly and steadily, maintaining control to keep the cage balanced throughout the ascent. Verify that the deflection is as expected.
6. Monitor the stability and adjust the position and any potential swing or rotation of the rebar cage as it is lifted slowly in a horizontal position.
7. Transition the cage to vertical configuration by gradually raising the load line at the head of the cage. Simultaneously, lower the load line supporting the tail of the cage, initiating the upending motion. Proper control and manipulation of the main and auxiliary lines facilitate a gradual transition from a horizontal to a vertical configuration.
8. Position the rebar cage over the designated hole or placement area. Lower the cage slowly and carefully, maintaining a controlled descent to prevent any damage or accidents. If the cage will

be supported on shoes at the base of the hole, it is recommended to also confirm column stability of the cage within the hole, and specify spacer wheel placement accordingly.

It is important to note that this outline provides a general overview of the procedure and does not delve into all possible details. The actual lifting process will involve additional safety practices and variations depending on specific project requirements, crane capabilities, and site conditions. Further information on the rigging of rebar cages is available in the Rigging Engineering Basics book by J.K. Anderson [9].



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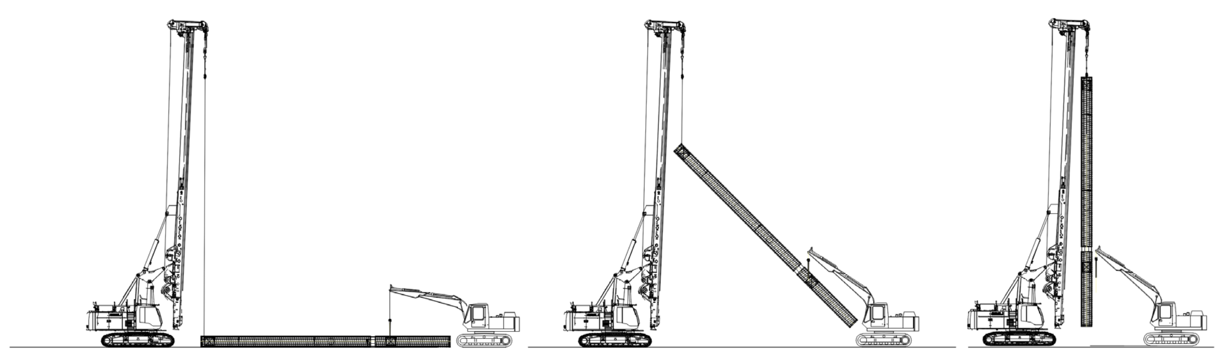

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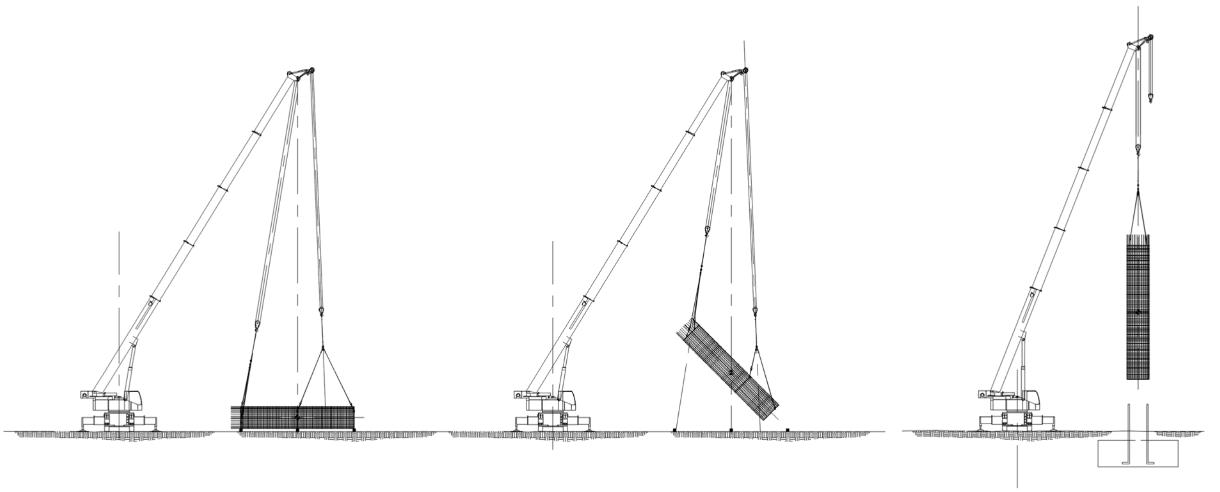
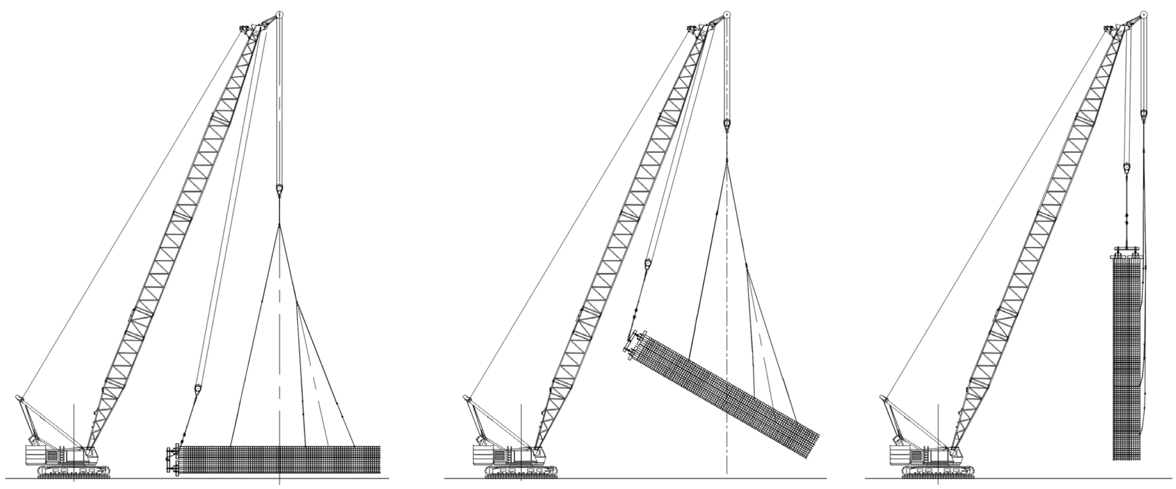
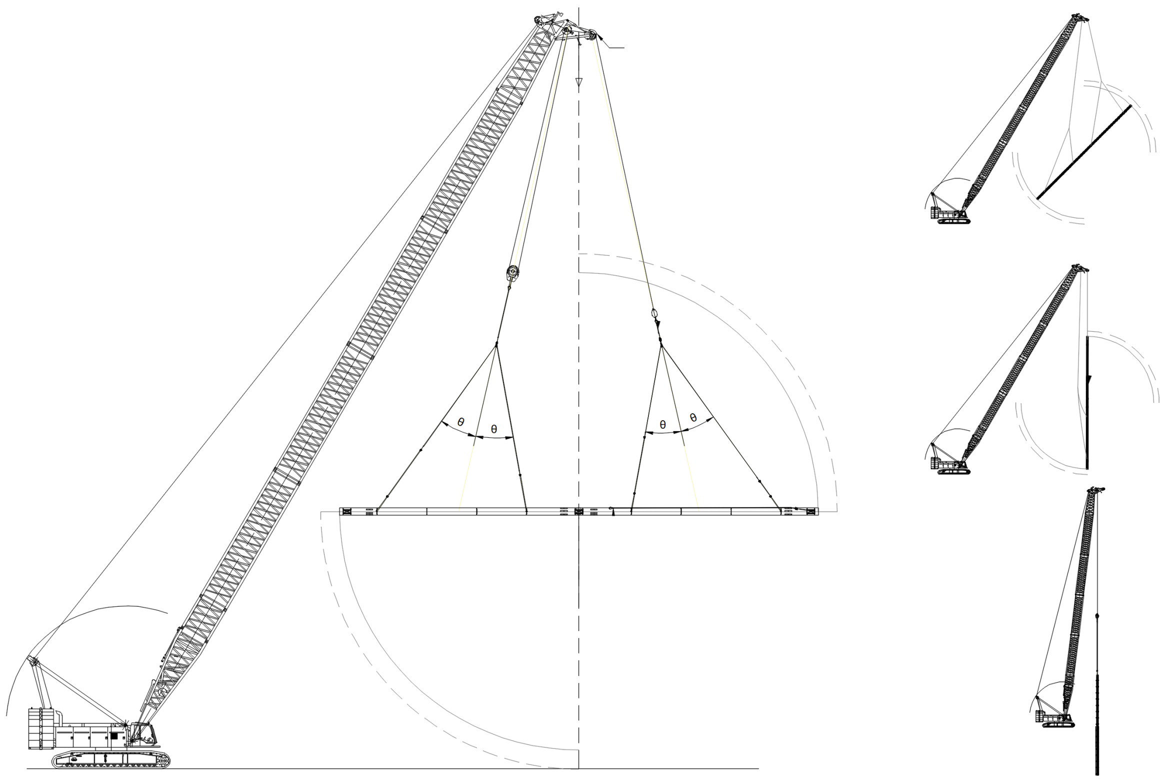


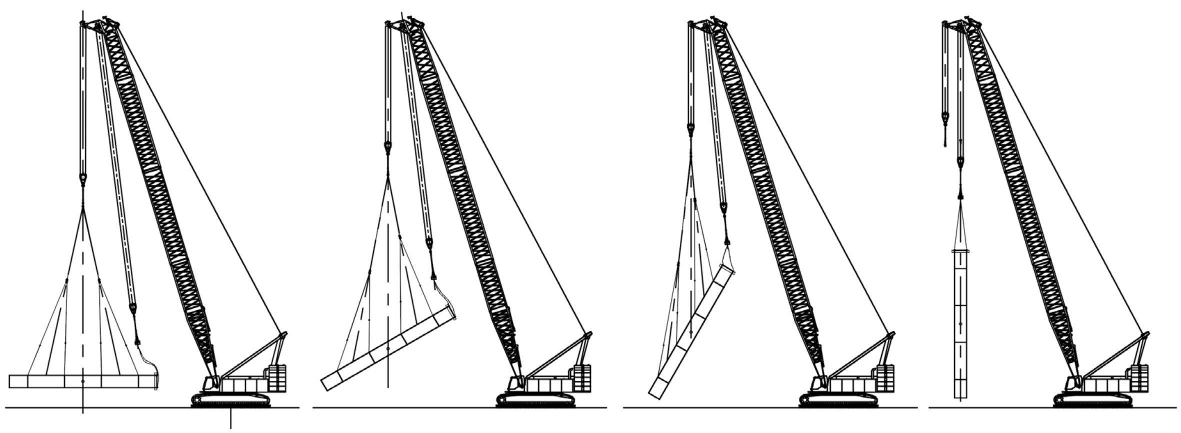
(c)



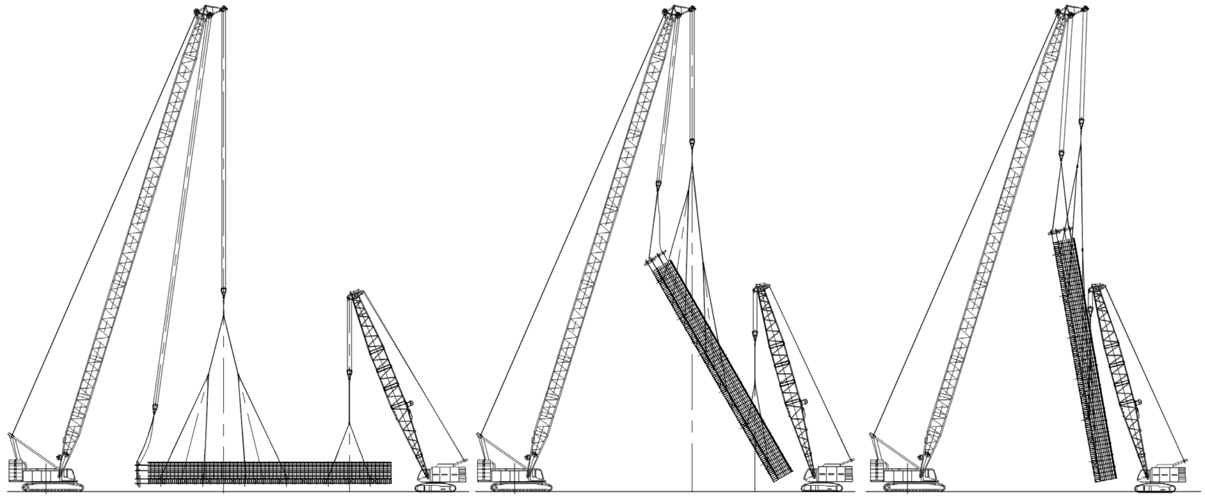
(d)



(e)



(f)



(g)

Fig. 14. Schematic examples of upending procedure: (a) Two pick-up points with one crane, (b) Two pick-up points with a drill rig and an excavator, (c) three pick-up points with one crane, (d) four pick-up points with one crane (method 1), (e) four pick-up points with one crane (method 2), (f) five pick-up points with one crane, (g) seven pick-up points with two cranes.

8 Design Examples

Disclaimer: The Design Examples provided in this section are provided to present the analytical design process and do not reflect the recommended locations for pick-up points or the analysis requirements for cages with more than two supports as described in Section 6.2.

8.1 Example 1

Determine the pick-up points, and number and placement of U-bolt connectors for a rebar cage with length of 25′ and no internal stiffening elements. The cage consists of 16#11 longitudinal rebars and #8 hoops as transverse rebars, spaced at 6-inch intervals, with an outer-to-outer diameter of 4′.

Solution:

Step 1: Specify the properties of the rebar cage.

$n = 16$, $D_c = 4'$, $D_r = 1.41''$ (#11), $\rho = \frac{16\times1.56}{\pi\times\frac{48^2}{4}} = 1.4\%$, $\rho_s = \frac{\pi\times48\times0.79}{\pi\times\frac{48^2}{4}\times6} = 1.11\%$, Total weight of the first cage $W = 4.65$ kip

Step 2: Determine U-bolt placement and pick-up points.

The spacing between tied-hoops is selected to be $8'$ with the first hoop at the top of the cage to be a tied-hoop. This will result in the configuration shown in Fig. 15. On each tied-hoop, four U-bolts should be installed at the intersections with the pick-up bars, hence, $C = \frac{4}{16} = 0.25$. The construction team requested that the cage be lifted from its ends; thus, the pick-up span is $l = 24'$.

Note that this example shows pick-up points at the cage ends, which is not optimal for cage deflection and not recommended. Wherever practical, select pick-up point locations to optimize cage deflections per recommendations in Section 4.

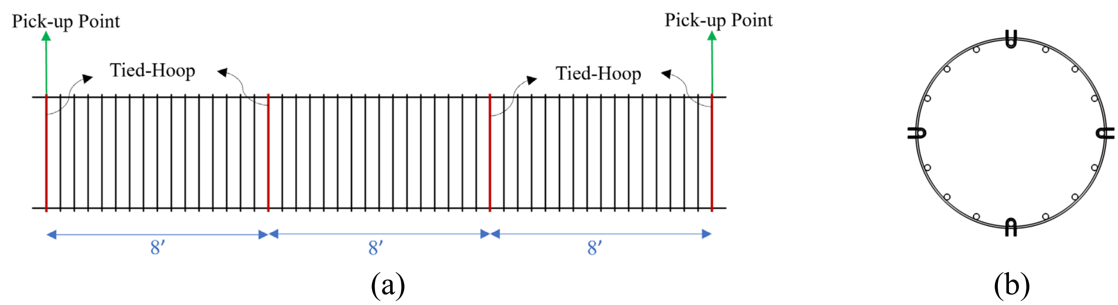


Fig. 15. (a) Pick-up points and U-bolt placement layout, (b) tied-hoop cross section for Example 1.

Step 3: Develop simplified equivalent beam model of the rebar cages by calculating rebar cage stiffness parameters, EI and GA_s.

$$I = n \cdot D_r^4 \cdot (0.06 + 0.04 \cdot C^{0.79}) = 4.68\ in^4 \tag{1}$$

$$A_s = \rho^{1.54} \cdot \rho_s^{0.04} \cdot \frac{(0.25 + 0.43 \cdot C)}{100} \cdot D_c^2 = 9.5 \times 10^{-3}\ in^2 \tag{2}$$

Step 4: Model and solve the simplified equivalent beam model.

The simplified equivalent beam model is developed using SAP2000 software based on the procedure described in section 6.2. A linear-elastic Timoshenko beam is modeled using stiffness parameters (EI and GA_s) calculated in the previous step. To address the geometric nonlinearity requirements (i.e., large deformation), the nonlinear static analysis option is selected within the load case window. Also, in the "Geometric nonlinearity Parameters" tab, the "P-Delta plus Large Displacement" option is activated. Note that the axial area is equal to the sum of the area of the longitudinal rebars, which is equal to $16 \times 1.56 = 24.96$ in^2. The pick-up points are modeled as simple supports, with one designated as a hinge support and the other as a roller support. The weight of the rebar cage is defined as a uniformly distributed load along the length of the simplified equivalent beam as $q = \frac{4650}{25} = 186$ lb/ft. Table 2 shows the result of the analysis.

Table 2. SAP2000 analysis result

Model	Total number of U-bolts	Maximum deflection in	Deflection limit criteria in	Deflection limit condition
25-ft cage	16	11.1 (at mid-span)	$0.1 \cdot l = 28.4$	Satisfied

8.2 Example 2

Determine the pick-up points, and number and placement of U-bolt connectors for a rebar cages with 41′ length without internal stiffening element and with section properties similar to the rebar cage of Example 1.

Step 1: Specify the properties of the rebar cage.

$n = 16$, $D_c = 4'$, $D_r = 1.41''$ (#11), $\rho = \frac{16\times1.56}{\pi\times\frac{48^2}{4}} = 1.4\%$, $\rho_s = \frac{2\pi\times24\times0.79}{\pi\times\frac{48^2}{4}\times6} = 1.0\%$, Total weight of the first cage $W = 7.66$ kip

Step 2: Determine U-bolt placement and pick-up points.

The tied-hoops are spaced at 8-foot intervals, with the first hoop positioned at the top of the cage as a tied-hoop as depicted in Fig. 16. At each tied-hoop, four U-bolts are to be installed at the intersections with the pick-up bars, resulting in a ratio of $C = \frac{4}{16} = 0.25$. The construction team requested that the cage be lifted from its ends, thereby setting the pick-up span at $l = 40'$.

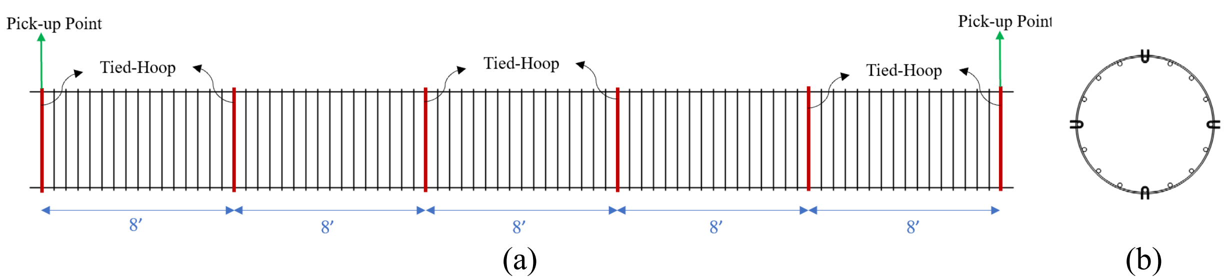


Fig. 16. (a) Pick-up points and U-bolt placement layout, (b) tied-hoop cross section for Example 2 (initial design).

Step 3: Develop simplified equivalent beam model of the rebar cages by calculating rebar cage stiffness parameters, EI and GA_s.

$$I = n \cdot D_r^4 \cdot (0.06 + 0.04 \cdot C^{0.79}) = 4.68\ in^4 \tag{3}$$

$$A_s = \rho^{1.54} \cdot \rho_s^{0.04} \cdot \frac{(0.25 + 0.43 \cdot C)}{100} \cdot D_c^2 = 9.5 \times 10^{-3}\ in^2 \tag{4}$$

Step 4: Model and solve the simplified equivalent beam model.

The simplified equivalent beam model is developed based on the procedure described in section 6.2. Table 3 shows the result of the SAP2000 analysis.

Table 3. SAP2000 analysis result

Model	Total number of U-bolts	Maximum deflection in	Deflection limit criteria in	Deflection limit condition
41-ft cage	24	70.4 (at mid-span)	$0.1 \cdot l = 48$	Not satisfied

The deflection of the rebar cage exceeds the deflection limit criteria. In order to rectify this, the pick-up points have been adjusted as illustrated in Fig. 17. Consequently, the new pick-up span is set at $l = 32'$. The construction team will need to be notified that they cannot pick up the cage from the ends, and that the tailing equipment will need to be able to reach high enough to provide the overhang as required for the new pick-up point locations.

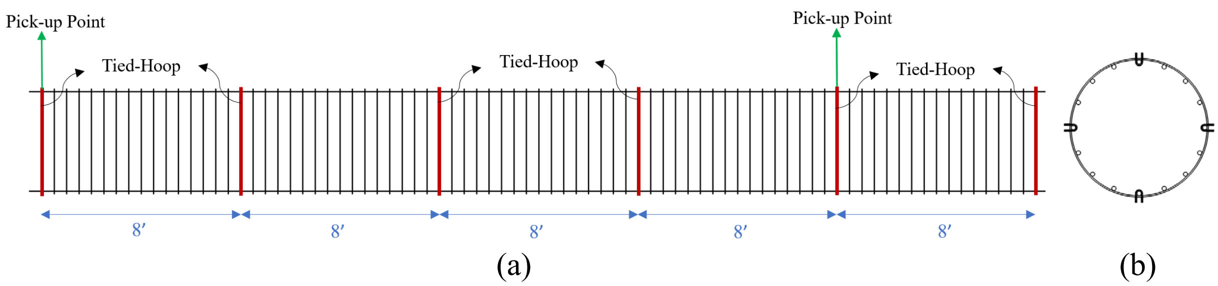


Fig. 17. (a) Modified pick-up points and U-bolt placement layout, (b) tied-hoop cross section for Example 2 (updated design).

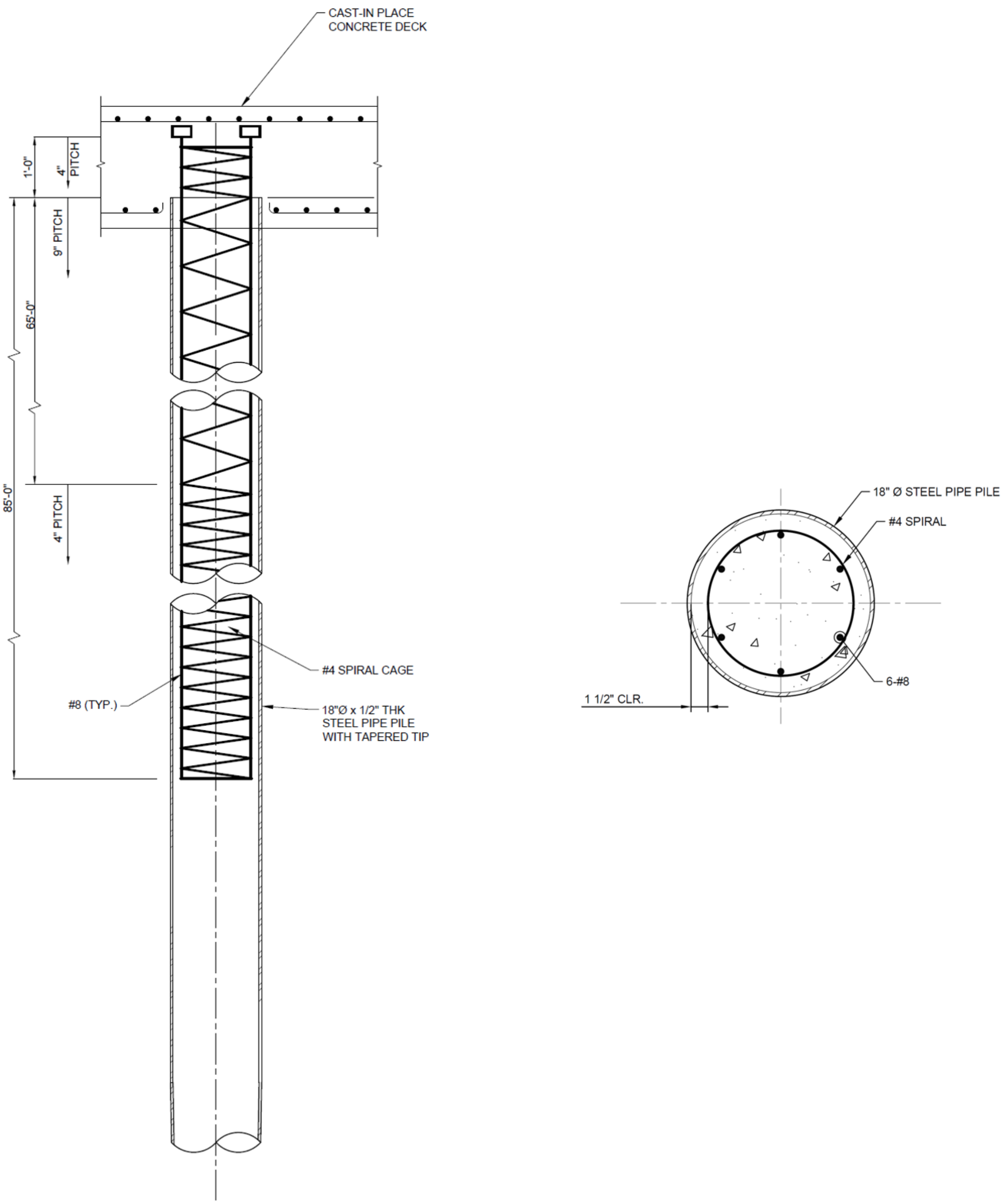
As the cross-section and number of U-bolts remain unchanged, there is no need to repeat Step 3. Hence, only Step 4 is repeated. The simplified equivalent beam model has been developed, and the results of SAP2000 analysis are provided in Table 4.

Table 4. SAP2000 analysis result

Model	Total number of U-bolts	Maximum deflection in	Deflection limit criteria in	Deflection limit condition
41-ft cage	24	27.5	$0.1 \cdot l = 38.4$	Satisfied

8.3 Example 3

Determine the pick-up points, number and placement of U-bolt connectors for the 86-feet spiral rebar cage presented in Fig. 18.



(a) (b)

Fig. 18. (a) Detail of 86-feet spiral rebar cage, (b) cross section.

Note that this rebar cage is outside the specified specifications in this guideline with only 6 longitudinal rebars and diameter of 15 inches (less than minimum of 4 feet diameter specified in Section 4). As a result, some of the recommendations outlined in Section 4 may not be applicable. Additionally, more than two pick-up points are needed, which would require a complex analysis of the combined effects of rigging/rolling hitches and cage stiffness. Pick-up points are modeled as rigid supports in this example only, for the purposes of illustrating that the deflections obtained from the presented simplified beam method match closely with those obtained from more advanced numerical models of the cage.

Step 1: Specify the properties of the rebar cage.

$n = 6,\ D_c = 15'',\ D_r = 1''(\#8),\ \rho = \frac{6\times 0.79}{\pi\times\frac{15^2}{4}} = 2.7\%,\ \rho_s = \frac{\pi\times 15\times 0.2}{\pi\times\frac{15^2}{4}\times 9} = 0.6\%$ (considered a #4 spiral with a uniformly spaced coil pitch of 9”), $W = 3.5$ kip.

Step 2: Determine U-bolt placement and pick-up points.

Two longitudinal rebars are designated as pick-up bars on each side of the cage, as shown in Fig. 19b. The spacing between tied spiral is selected to be 8-foot-3-inch with the first spiral with U-bolts to be at 2’3” from the top of the rebar cage. On each tied spiral, two U-bolts should be installed at the intersections with the pick-up bars, hence, $C = \frac{2}{6} = 0.33$. Four pick-up points are selected with a 24-foot-9-inch interval ($l = 24.75'$) as shown in Fig. 19.

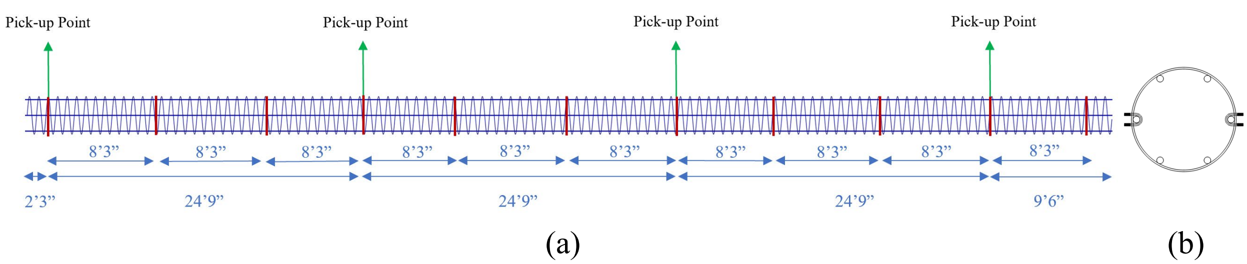


Fig. 19. (a) Pick-up points and U-bolt placement layout, (b) cross section for Example 3.

Step 3: Develop simplified equivalent beam model of the rebar cages by calculating rebar cage stiffness parameters, EI and GA_s:

$$I = n \cdot D_r^4 \cdot (0.06 + 0.04 \cdot C^{0.79}) = 4.65 \times 10^{-1}\ in^4 \tag{5}$$

$$A_s = \rho^{1.54} \cdot \rho_s^{0.04} \cdot \frac{(0.25 + 0.43 \cdot C)}{100} \cdot D_c^2 = 2.74 \times 10^{-3}\ in^2 \tag{6}$$

Step 4: Model and solve the simplified equivalent beam model.

The simplified equivalent beam model is developed based on the procedure described in section 6.2. Table 5 and Fig. 20 show the result and deformed shape of the SAP2000 analysis.

Table 5. SAP2000 analysis result

Model	Total number of U-bolts	Maximum deflection in	Deflection limit criteria in	Deflection limit condition
86-feet spiral cage	22	13.0	$0.1 \cdot l = 29.7$	Satisfied

Fig. 20. Deformed shape of the beam model as analyzed in SAP2000.

Warning! Actual deflected shape will be significantly different than that shown in the results of this example, once the effects of rigging/rolling hitches are taken into account in the model. This example with multiple rigid supports is shown for simplicity only. Lifts with more than two pick-up points cannot be modeled with rigid supports.

8.4 Example 4

Determine the pick-up points, and number and placement of U-bolt connectors for a rebar cage with length of 81′ and no internal stiffening elements. The cage consists of 36#11 longitudinal rebars and #8 hoops as transverse rebars, spaced at 6-inch intervals, with an outer-to-outer diameter of 5′6″.

Step 1: Specify the properties of the rebar cage.

$n = 36$, $D_c = 5.5'$, $D_r = 1.41''$ (#11), $\rho = \frac{36\times 1.56}{\pi\times\frac{66^2}{4}} = 1.6\%$, $\rho_s = \frac{\pi\times 66\times 0.79}{\pi\times\frac{66^2}{4}\times 6} = 0.8\%$, Total weight of the first cage $W = 31.1$ kip.

Step 2: Determine U-bolt placement and pick-up points.

The spacing between tied-hoops is selected to be $10'$ with the first hoop at the top of the cage to be a tied-hoop. This will result in the configuration shown in Fig. 21a. On each tied-hoop, six U-bolts should be installed including four U-bolts at the intersections with the pick-up bars, hence, $C = \frac{6}{36} = 0.17$ (see Fig. 21b). Three pick-up points are selected with a 30-foot interval ($l = 30'$) as shown in Fig. 21.

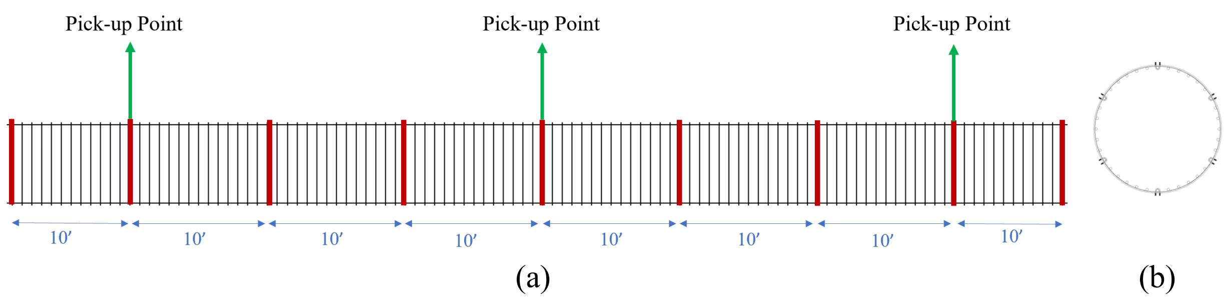


Fig. 21. (a) Pick-up points and U-bolt placement layout, (b) cross section for Example 4.

Step 3: Develop simplified equivalent beam model of the rebar cages by calculating rebar cage stiffness parameters, EI and GA_s:

$$I = n \cdot D_r^4 \cdot (0.06 + 0.04 \cdot C^{0.79}) = 10.0\ in^4 \quad (7)$$

$$A_s = \rho^{1.54} \cdot \rho_s^{0.04} \cdot \frac{(0.25 + 0.43 \cdot C)}{100} \cdot D_c^2 = 1.91 \times 10^{-2}\ in^2 \quad (8)$$

Step 4: Model and solve the simplified equivalent beam model.

The simplified equivalent beam model is developed based on the procedure described in section 6.2. Table 6 shows the result of the SAP2000 analysis.

Table 6. SAP2000 analysis result

Model	Total number of U-bolts	Maximum deflection in	Deflection limit criteria in	Deflection limit condition
86-feet spiral cage	54	8.3 (at mid-spans)	$0.1 \cdot l = 36$	Satisfied

Similar to the previous example, the effects of rigging equalizer tension (at the middle pick-up point) have not been considered. The actual deflected shape will be different than that shown in the results of this example. This example with three rigid supports is shown for simplicity only. Lifts with more than two pick-up points cannot be modeled with rigid supports.

9 Summary

This guideline presents a systematic fabrication and design approach for rebar cages using mechanical U-bolt connectors to ensure their stability and safety during the lifting process. The purpose of this guideline is to provide a straightforward tool for determining the layout of U-bolts and lifting points, and to quickly estimate rebar cage deflection during lifting. The guideline is based on a comprehensive experimental and analytical research campaign that investigated the behavior of rebar cages reinforced with U-bolt connectors. The research aimed to promote the adoption of U-bolt connectors as a viable solution to improve the overall safety of rebar cages not only during lifting, but in the future for all phases of construction.

Disclaimer

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Appendix 1: Terminology and Definitions

The terminology and definitions presented in this section are based on the ASCE Rebar Cage Construction and Safety publication [10] as well as inquiries from experienced rebar cage practitioners.

- Longitudinal Rebar or Vertical Rebar: Reinforcing bar placed along the length of the rebar cage and tied or connected to the hoops or spirals.
- Hoop (Round Band): Circular-formed rebar forming the concentric rings of the rebar cages. Welded hoops were considered for this analysis.
- Spirals: Reinforcing steel for concrete confinement, shaped like a corkscrew and used in addition to or instead of hoops.
- Transverse Rebar: Transverse rebar includes hoops (bands) or spirals.
- Pick-up Bars: Longitudinal bars that transfer the cage weight to the rigging during lifting from the horizontal to the vertical position.
- Template Hoop/Band: Sparsely spaced rebar ring used to rough-in the diameter of a rebar cage during fabrication. Also referred to as "frame bands."
- Tied-hoops: Hoops spaced at specified intervals, tied to the longitudinal rebar at all intersections.
- Pick-up Point: The intersections of pick-up bars and the hoops/bands that are securely tied to all the longitudinal (vertical) rebars and used to connect to crane rigging for pick up.
- Pick-up Span: The distance between each two adjacent pick-up points.
- Pick-up Hoops: Hoops located at pick-up point location.
- Z-bar: An internal stiffening element inside a rebar cage consisting of a leading leg tied to the longitudinal bars, a diagonal brace across the diameter of the cage, and another leg tied to the longitudinal bars on the opposite side.
- X-bracing: An arrangement of Z-bar or welded diagonals to form an "X" in the cross-section of a rebar cage.
- Square bracing: An arrangement of Z-bar to form a square in the cross-section of a rebar cage.
- Internal Stiffening Elements: Diagonal elements (X-bracing, square bracing, or similar devices) and inner rings, tied or welded together, used to stabilize the rebar cage during site handling and construction.

- Inner Ring or Band: Template hoops (Template bands) or rings of internal stiffening elements surrounded by longitudinal bars.
- Wagon Wheels: Stiffened rings used to prevent ovalization and in-plane distortion of rebar cages.

Appendix 2: Types of Tie-Wire Connection

Numerous types of tie-wire connections are used in rebar cage fabrication. Illustrations of some of the most common types of tie-wire are shown in Fig. 22.

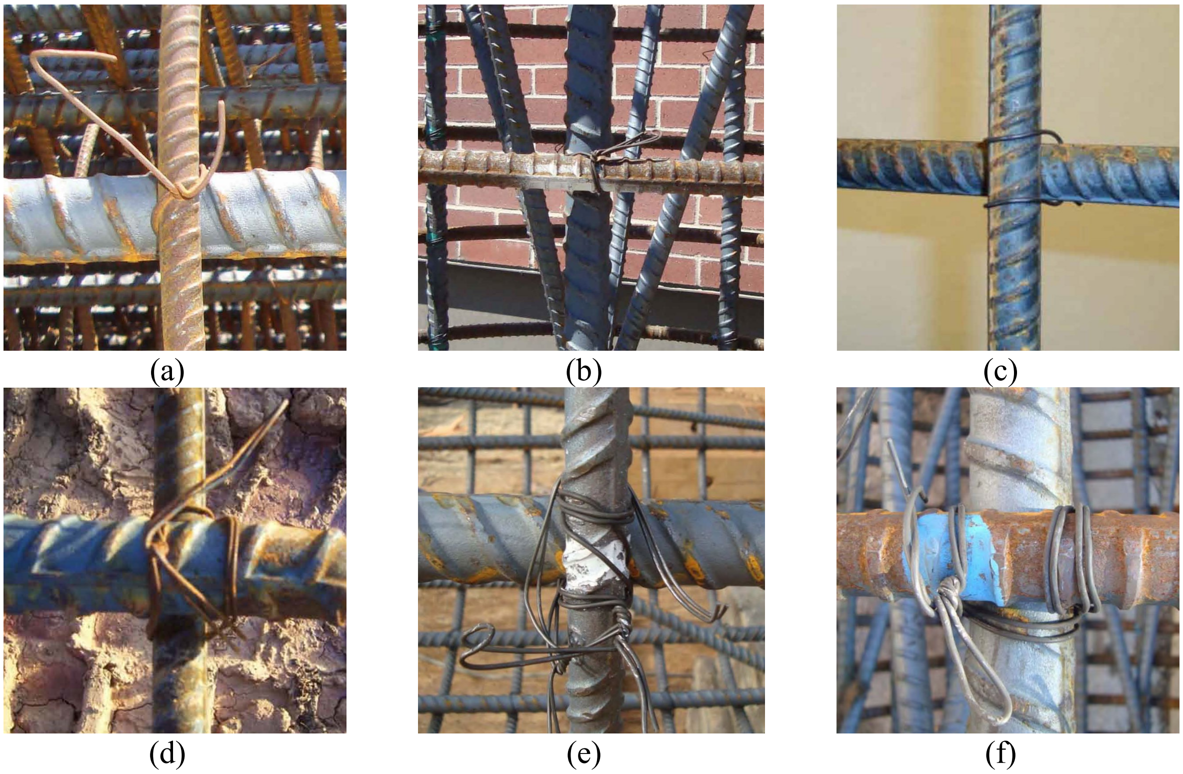

Fig. 22. Different tie-wire connection types: (a) Single snap, (b) Double snap, (c) Single-U, (d) Double-U, (e) Column tie, and (f) Wrap and saddle. Figures are taken from [1].

References

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