University of Nevada, Reno

Research Summary: Application of U-bolt Connector for Improving the Safety of Rebar Cages

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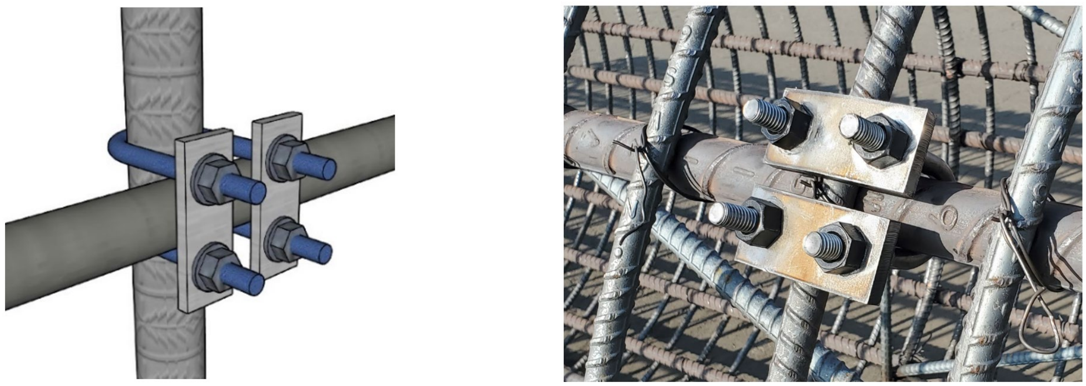
1 Introduction

Prefabricated rebar cages are widely used in reinforced concrete structures for both above-ground and below-ground construction. Examples include bridge piers, slurry wall foundations, and drilled shafts (cast-in drilled hole piles). These temporary structures typically consist of longitudinal and transverse bars that are connected using tie-wires. Despite the increasing demand for rebar cages in the construction industry, there is still limited understanding of their behavior and structural performance. The lack of engineering knowledge about rebar cages has contributed to an elevated risk of failure during various construction stages, resulting in safety hazards, project delays, and increased construction costs. The experimental-analytical investigations conducted by Builes-Mejia et al. [1], [2] showed that the root cause of rebar cages failure is initiated by tie-wire connection failure, making them the "weak links" in the rebar cages. As a result, alternative methods for connecting the rebars have been explored, such as utilizing mechanical connectors.

This research project investigated the application of mechanical U-bolt connectors to replace traditional tie-wire connections at selected locations along the rebar cages to improve the overall stability of the cage. A U-bolt connector consists of two U-shaped threaded bolts and two plates, as illustrated in Fig. 1. Initially, a comprehensive experimental campaign was conducted to establish the mechanical properties of U-bolt connectors for cross-bar connections. The force-deformation responses of U-bolt connections were determined under different degrees of freedom (DOFs) and conditions. Based on these experimental results, idealized bilinear models were developed to represent U-bolt connections for use in computational models [3]. Furthermore, full-scale experimental tests were performed on underground pile-shaft rebar cages with mechanical U-bolt connectors to investigate the behavior of rebar cages reinforced with U-bolt connectors under common site handling conditions such as lifting and tilting. Subsequently, a detailed numerical model of the rebar cages was developed and calibrated using the experimental results. The models were then validated at both the structural and local scales. The validated numerical model demonstrated the ability to predict the complex response behavior of rebar cages with U-bolt connectors under site handling conditions, as well as traditional tie-wired rebar cages with internal stiffening elements. After that, to analyze the effect of physical parameters on rebar cage stiffness, parametric studies were conducted using the validated numerical model. Through dimensional analysis and parametric studies, analytical models were derived to characterize the stiffness properties of a rebar cage as a function of its physical properties. These derived stiffness properties can be used to develop a simplified beam model, enabling engineers to analyze the deflection of rebar cages under site loading conditions without relying on complex and expensive numerical models.



(a) (b)

Fig. 1. (a) Schematic view of U-bolt connection, (b) an assembled U-bolt connector for a cross-bar connection in a rebar cage.

The primary objective of this project was to investigate the potential applications of mechanical U-bolt connectors for cross-bar connection in below-grade and above grade rebar cages during site handling process (i.e., lifting, tilting). Based on this, the research plan was designed to study the stiffness properties of circular rebar cages. It became clear during the investigations that mechanical connectors can significantly improve strength and stability of rebar cages by enhancing the integrity of the connection and load-transfer mechanism between rebar components and eliminating the premature failure of tie-wire connections, which are the “weak links” in a rebar cage. During the project, it was determined that there is a need for a follow up research project to focus on determining the ultimate strength and failure mechanism of rebar cages reinforced with mechanical connectors, which can enhance the engineering design practice. A factor of safety can then be applied to the ultimate strength, and the allowable shear and moment forces can be reliably determined. Furthermore, several practical questions still remain unanswered in design, handling, and construction of rebar cages that would require further investigations. These questions include the best practice for base-restraining and external bracing of above-grade rebar cages, behavior study of rectangular-shaped rebar cages for slurry and shear walls, guidelines on splicing rebar cages, and the potential application of other types of connector.

2 Component-Level Experimental Tests

To determine the mechanical properties of U-bolt connectors for cross-bar connections, component-level tests were conducted. The force-deformation responses of U-bolt connections in different degrees of freedom (DOFs) were investigated through a series of experiments. To define the DOFs at a cross-bar connection, a local coordinate system is defined, and DOFs in the x (normal), y (tangential), and z (vertical) directions was specified, as illustrated in **Error! Reference source not found.** [4]. The U-bolt material is ASTM A29/A108 Grade 1541 with the tensile yield stress of 720 MPa (105 ksi) and tensile strength of 830 MPa (120 ksi), and the plates are A36 steel. The dimensions of the mechanical connector U-bolt and plate are shown in Fig. 3. Rebar #11 was used as longitudinal and #8 as transverse bars. The tests were performed by an Instron 5985 Universal Testing Machine in a displacement-controlled mode. While the force is recorded through the machine's internal sensor, the connector deformation is measured using a synchronized MTS LX500 laser extensometer, which uses laser beams to measure the relative displacement between two reflectors installed on the rebars. The test setups are shown in Fig. 4

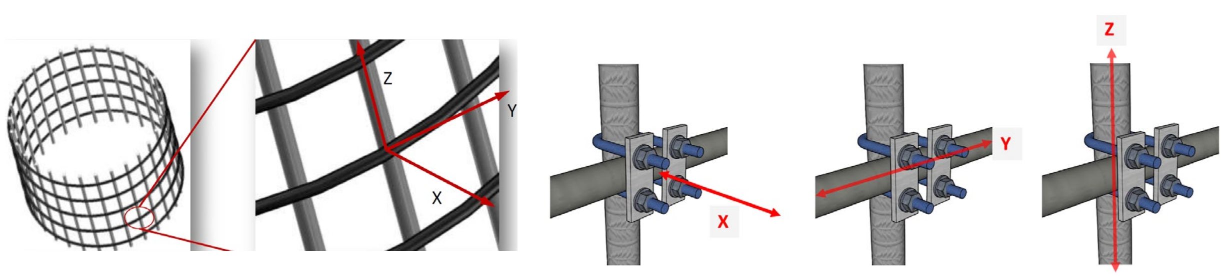


Fig. 2 : Local coordinate system at a cross-bar intersection in a rebar cage.

[5].

The force-deformation response of the U-bolt connection is presented in Fig. 5 [3]. For modeling purposes, the experimental force-deformation responses are idealized with bilinear models. Table 1 summarizes the results, including the effective elastic stiffness (K_e), the linear force limit (also referred to as the yield strength, F_y), the post-yield stiffness ratio (b), and post-yield stiffness (K_b, defined as $K_b = b \times K_e$). Details of component-level experimental tests along with their results, have been published in the ASCE Journal of Structural Engineering [3] and ASCE Construction Research Congress proceeding [4]. Additionally, a corresponding technical report [5] has been made available. Moreover, another type of mechanical connector known as Cage Clamp has also undergone investigation, with the results set to be published soon.

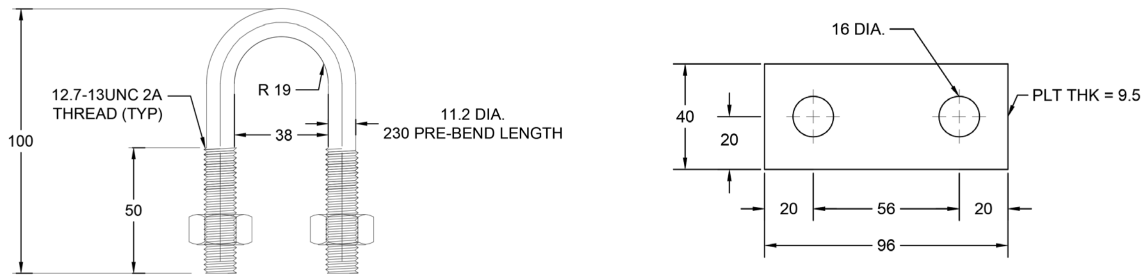


Fig. 3: Mechanical connector U-bolt and plate details (dimensions are in mm).

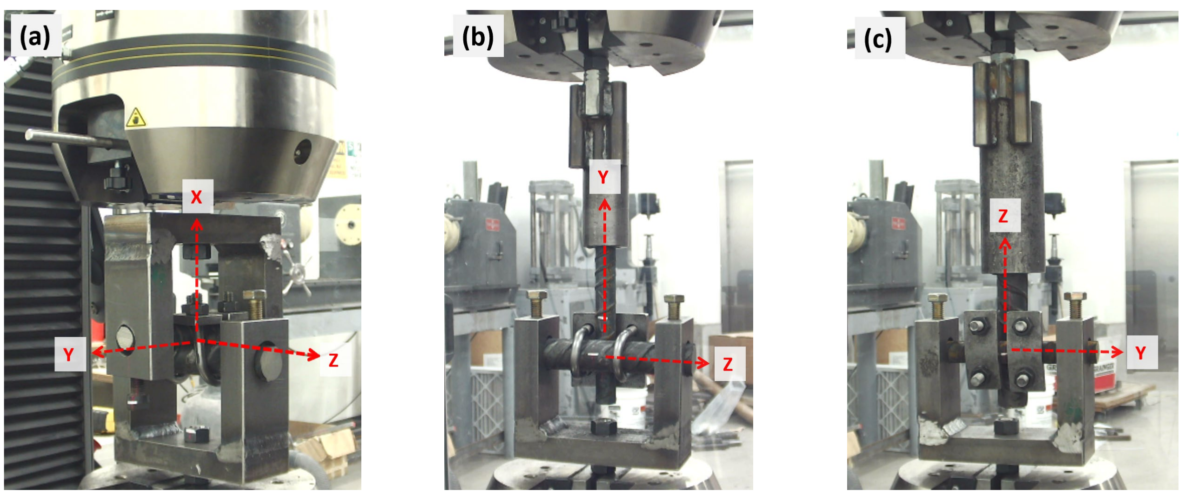


Fig. 4: Test setup in (a) normal direction, (b) tangential direction, and (c) vertical direction.

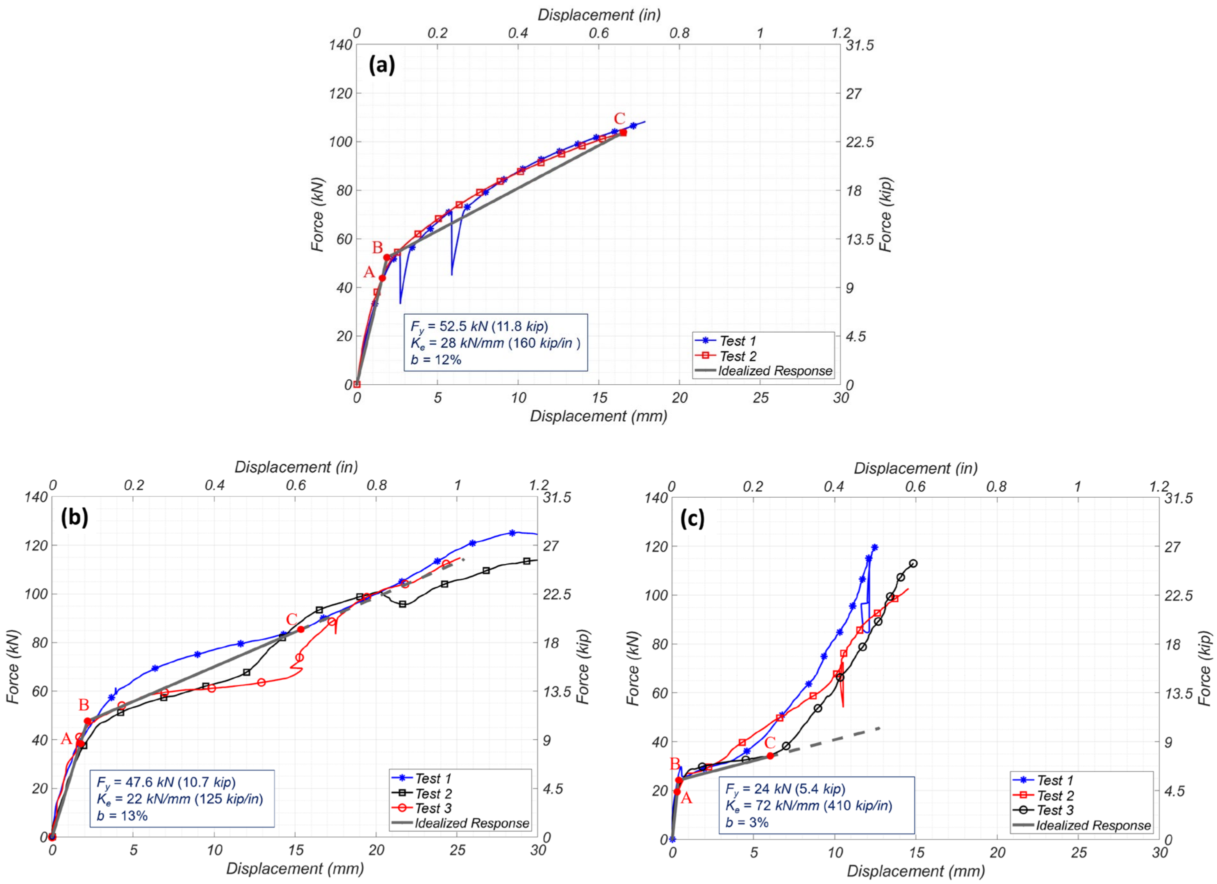


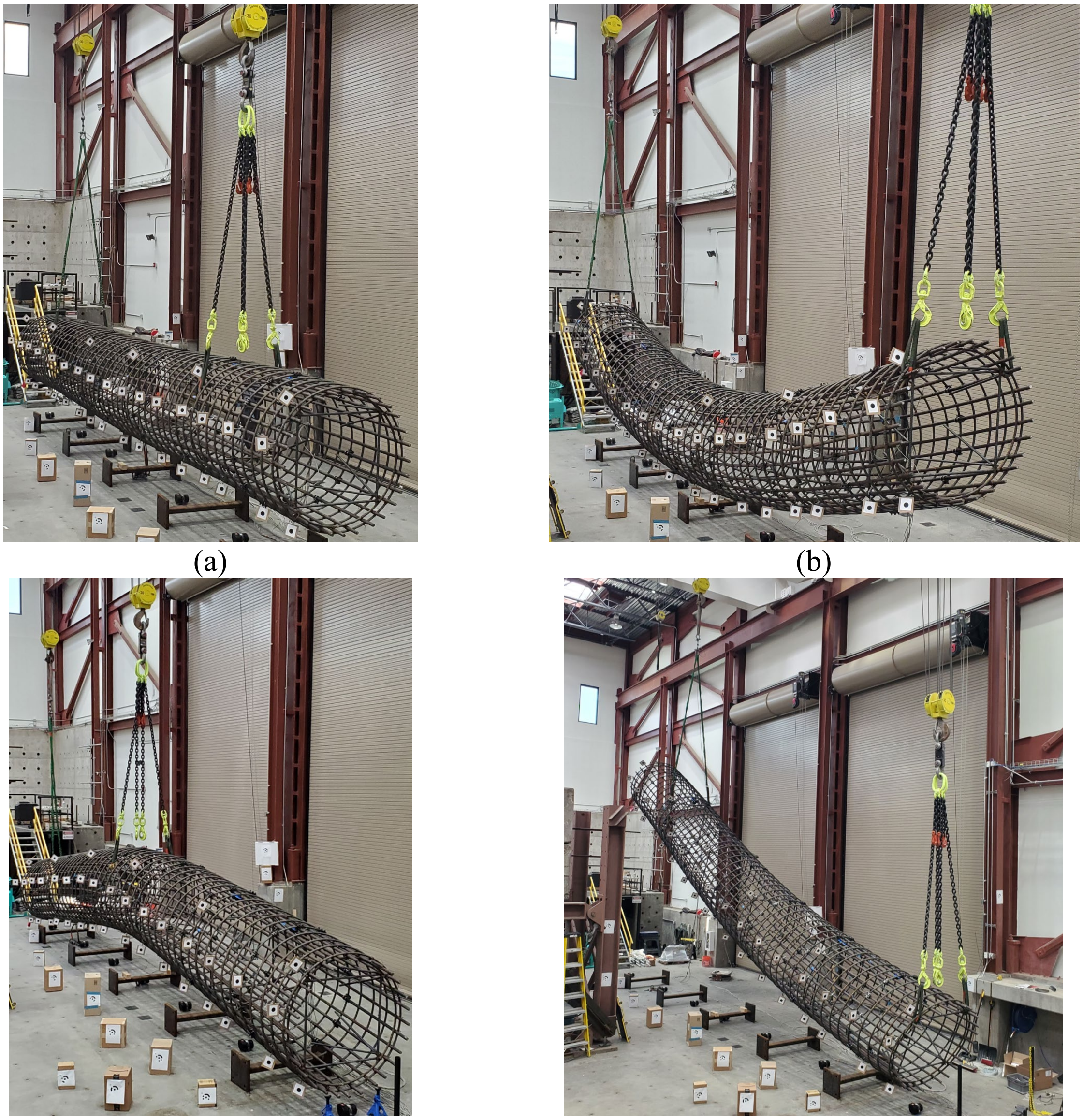
Fig. 5. Force-deformation response of U-bolt connection: (a) normal (x) direction, (b) tangential (y) direction, and (c) vertical (z) direction.

Table 1. Summary of the bilinear model parameters for U-bolt connections.

Rebar Condition	***DOF***	***K_e* kN/mm (kip/in)**	***F_y* kN (kip)**	***b (%)***	***K_b* kN/mm (kip/in)**
Longitudinal #11 and transverse #8 Ribbed Rebars	x	28 (160)	52.5 (11.8)	12	3.36 (19.2)
	y	22 (125)	47.6 (10.7)	13	2.86 (16.3)
	z	72 (410)	24 (5.4)	3	2.16 (12.3)

3 Full-Scale Experimental Tests

Full-scale experimental testing was performed on five 43-ft circular rebar cages with tie-wire and mechanical U-bolt connectors [6]. The objectives of full-scale tests were to investigate the behavior of rebar cages reinforced with U-bolt connectors under common site handling conditions (i.e., transportation, lifting, and tilting) and to generate data to develop, calibrate, and validate numerical models that can predict the response behavior of the rebar cages with U-bolt connectors. The testing specimens were fabricated based on the guidelines provided in the California Department of Transportation (Caltrans) Standard Specifications Section 52 [7]. The deflection profiles of the rebar cage specimens were measured through a non-contact optical method called target tracking Digital Image Correlation (DIC). Also, the local deformations of the cages were measured using string potentiometers. It was observed that the U-bolt connectors effectively kept the integrity of the rebar cages, and no failure or damage occurred in the specimens in any of the test scenarios, even under large deformations. The U-bolt connectors were inspected after each test scenario, and it was observed that they remained tight-fit without any slippage. The post-test numerical models revealed that tie-wired rebar cages (without internal stiffening elements) are susceptible to failure under gravity lifting loads. In contrast, both experimental and numerical findings demonstrated that rebar cages reinforced with U-bolt connectors remained intact and undamaged. This demonstrates the effectiveness of U-bolt connectors in reinforcing rebar cages and preventing failure under transport and site handling loads.



(a) (b) (c) (d)

Fig. 6. Testing of the rebar cages reinforced with U-bolt connectors without internal stiffening elements: (a) common practice, (b) pick-up from two-ends, (c) pick-up from center, (d) lift and tilt up to 40 degree.

4 Finite Element Modeling

Detailed finite element (FE) models of rebar cages were developed using the LS-DYNA FE simulation platform based on the experimental data obtained from component-level tests. The models include the geometry and detail of reinforcing bars, internal stiffening elements, tie-wires, and U-bolt connections. U-bolt and tie-wire connections are modeled using multilinear discrete spring elements. Through initial model simulations, it was observed that the model predictions are more flexible that the experimental results. Upon careful investigation , it was found out that discrepancies between the model predictions and experimental results are attributed to inaccurately modeled torsional stiffness of U-bolt connectors, as this parameter was not directly measured through physical experiments. A model inversion process was employed to estimate the torsional stiffness using the experimental results of selected test scenarios. The rotational stiffness of U-bolt connections was determined through a model updating process. An objective function was defined to quantify the discrepancies between measured and FE-predicted deformations. The numerical models were then cross-validated with the result of the rest of the test scenarios, showing reasonable agreement between the simulated and measured data. Additionally, the calibrated models were validated at local scales to ensure their accuracy and reliability, demonstrating their capability to capture the complex behavior of rebar cages reinforced with U-bolt connectors, as well as traditional tie-wired rebar cages with internal stiffening elements. Details of full-scale experimental tests and finite element (FE) modeling, along with their respective results, have been published in the Applied Sciences journal [6].

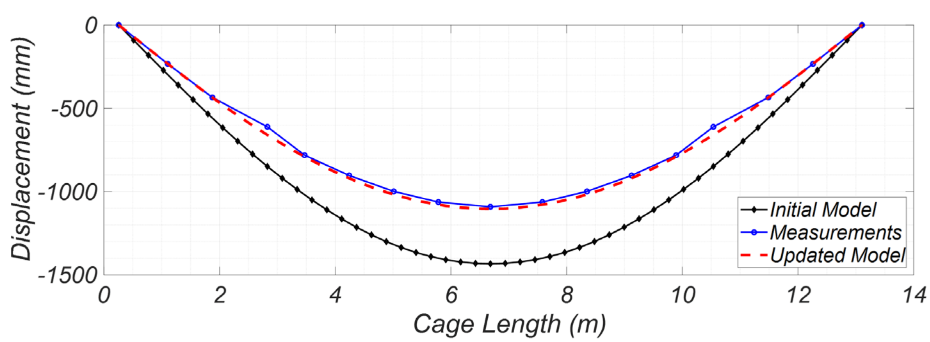


Fig. 7. Comparison of the deflection of one of rebar cages with the initial and updated model predictions.

Additionally, finite element models were developed to investigate the behavior of rebar cages without internal stiffening elements and with U-bolt connectors during transportation. It is worth noting that internal stiffening elements serve the purpose of maintaining stability during transport as well. The findings indicate that rebar cages may be safely transported without internal stiffening when constructed with the recommended quantities of U-bolts specified in the "Guidelines for Circular Rebar Cage Assembly with U-bolt Connectors”.

5 Analytical Investigation – Simplified Equivalent Beam Model of Rebar Cages

The validated models were used to perform parametric studies, wherein the physical properties of the rebar cage were systematically varied to analyze the corresponding changes in the behavior and deflection of rebar cages. The deflection profiles of rebar cage models were then fitted on the Timoshenko beam model, which account for both bending and shear deformations. By employing dimensional analysis, simplified models were derived to characterize the stiffness properties of the rebar cages as function of their physical properties as follows.

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

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

where,

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 number of longitudinal rebars fasten to tied-hoop using mechanical connectors to 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 to total cross-section area

ρ_s = transverse steel ratio, ratio of volume of transverse reinforcement to total volume of core confined by the transverse reinforcement, measured out-to-out of transverse reinforcement

D_c = diameter of the rebar cage, in

The derived stiffness properties namely “effective moment of inertia” and “effective shear area” can be used to develop a simplified equivalent beam model, which enables engineers to analyze rebar cages and estimate their deflection under site loading conditions without relying on complex and expensive numerical models. This model has significant implications, as it offers a rapid and easy method for analyzing the behavior of rebar cages using readily available structural analysis software..

Using the simplified equivalent beam model in conjunction with both experimental and numerical data, comprehensive design guidelines and best practices have been developed for the assembly of circular rebar cages using U-bolt connectors. These guidelines establish a systematic approach to fabrication and design, while also providing deflection limit criteria for rebar cages reinforced with U-bolt connectors. The guideline further encompasses information about the current state-of-the-practice assembly for tie-wired rebar cages, upending procedures and vertical placements, along with design examples for rebar cages with U-bolt connectors. The primary objective of these guidelines is to ensure the stability and safety of rebar cages during transportation and lifting. Additionally, it provides a straightforward tool for determining the layout of U-bolts and lifting points, enabling a quick estimation of rebar cage deflection during lifting.

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.

Additionally, it's worth noting 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, and practicing engineers are advised to consider CSL deflection accordingly.

Furthermore, 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 existing equations, in their current form, are not suitable for calculating section properties of cages with this configuration. Further research into applicable equations has been recommended by stakeholders, and development is anticipated with industry participation.

6 Concluding Remarks

This research project took the first step in addressing the critical need for a deeper understanding of the behavior and structural performance of prefabricated rebar cages. With a specific focus on enhancing the structural behavior of rebar cages, the study investigated the application of mechanical U-bolt connectors as an innovative solution. Component-level and full-scale experimental tests were performed to generate data for developing, calibrating, and validating finite element models of rebar cages. The validated model was then utilized for parametric studies and dimensional analysis, which led to the development of a simplified equivalent beam model. This model enables engineers to analyze the deflection of rebar cages under site loading conditions without the need for complex numerical simulations.

The research findings highlight the effectiveness of U-bolt connectors in improving the stability and strength of rebar cages. The study contributes to enhancing the understanding of rebar cage behavior, mitigating the risk of failure during construction, and ultimately improving safety, reducing project delays, and lowering construction costs.

Furthermore, the developed simplified beam model provides a practical and cost-effective tool for engineers to calculate the deflection of rebar cages using readily available software. It offers valuable insights for the design and analysis of prefabricated rebar cages, facilitating efficient and reliable construction practices. Additionally, it has been observed that pick-up locations are the most influential factor in reducing deflection, which is an important variable for practicing engineers. This research project advances the knowledge and understanding of rebar cage behavior. Its practical implications for the construction industry promote safer and more efficient construction practices.

In addition, the research has yielded the following products.

1- Guidelines for Circular Rebar Cage Assembly with U-bolt Connectors.
2- Best Practice Manual for Circular Rebar Cage Assembly with U-bolt Connectors.
3- Journal Papers:
   - M. Vahedi, H. Ebrahimian, and A. M. Itani, "Experimental Investigation of U-Bolt Connectors for Application in Rebar Cages," *J. Struct. Eng.*, vol. 149, no. 1, p. 4022216,

2023, doi: 10.1061/JSENDH.STENG-11381.

- M. Vahedi, H. Ebrahimian, and A. M. Itani, "Full-Scale Testing and Analytical Modeling of Rebar Cages Reinforced with Mechanical U-Bolt Connectors," Appl. Sci., vol. 13, no. 14, p. 8113, Jul. 2023, doi: 10.3390/app13148113.

4- Other Publications:

- M. Vahedi, H. Ebrahimian, and A. M. Itani, *CCEER-22-02: Response and Behavior Of Mechanical Connectors For Application In Rebar Cages: An Experimental Study*, University of Nevada, Reno, 2022.
- M. Vahedi, H. Ebrahimian, and A. M. Itani, "Experimental Study of Mechanical Connectors for Application in Rebar Cages," in Construction Research Congress 2022, 2022, pp. 171–177. doi: 10.1061/9780784483954.018.
- Project website accessible at: https://packpages.unr.edu/rebarcageproject/.

While the project was focused on the application of mechanical connector in rebar cages with an emphasize on understanding the deformation and stiffness properties of rebar cages, there is a clear need for a follow up research project to investigate strength-based design guidelines for different types of rebar cages (above- and below-grade, circular and rectangular) and under different loading conditions that may be applied during the construction process.

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