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”Reinforcement Congestion in Cast-in-Place Concrete”

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Reinforcement Congestion in Cast-in-Place Concrete

Allowances for construction tolerances and for adequate placement and consolidation

by James Klinger, Oscar R. Antommattei, Aron Csont, Trevor Prater, Michael Damme, and Bruce A. Suprenant

Since its 1983 edition,[1] the ACI 318 Code Commentary has cautioned designers to avoid reinforcement congestion in earthquake-resistant structures. And since its 1999 edition,[2] the ACI 318 Code has required designers to consider fabrication and placement tolerances at anchorage zones for post-tensioning tendons. The relevant sections of ACI 318-19[3] state:

"**R18.2.2** Analysis and proportioning of structural members

In selecting member sizes for earthquake-resistant structures, it is important to consider constructability problems related to congestion of reinforcement. The design should be such that all reinforcement can be assembled and placed in the proper location and that concrete can be cast and consolidated properly. Using the upper limits of permitted reinforcement ratios may lead to construction problems."

"**25.9.5** Reinforcement detailing

25.9.5.1 Selection of reinforcement size, spacing, cover, and other details for anchorage zones shall make allowances for tolerances on fabrication and placement of reinforcement; for the size of aggregate; and for adequate placement and consolidation of the concrete."

While the engineer is responsible for detailing reinforcement, we've been unable to find Commentary guidance on reasonable detailing practice or acceptability of details. Compliance is, therefore, open to subjective interpretation. However, it's clear that many designers are struggling to meet either the spirit of the Commentary or the letter of the Code (see Fig. 1).

In addition, constructability requirements and recommendations should not be limited only to earthquake-resistant structures or post-tensioning tendon anchorage zones. Engineers should provide an allowance for construction tolerances and consider the need for adequate placement and consolidation of concrete for all designs.

This article provides information on design and detailing prerequisites, reinforcement congestion economics, allowance recommendations related to congestion of reinforcement, and proposed Code and Commentary language with respect to constructability.

ACI 309R Constructability Recommendations for Design and Detailing

The ACI 318-77 Commentary, Section 5.4,[4] provided the first reference to ACI 309R[5]:

"Recommendations for consolidation of concrete are given in detail in 'Recommended Practice for Consolidation of

Fig. 1: Examples of reinforcement assemblies that created placement challenges for the contractor: (a) an earthquake-resistant wall; and (b) an anchorage zone for post-tensioning tendons

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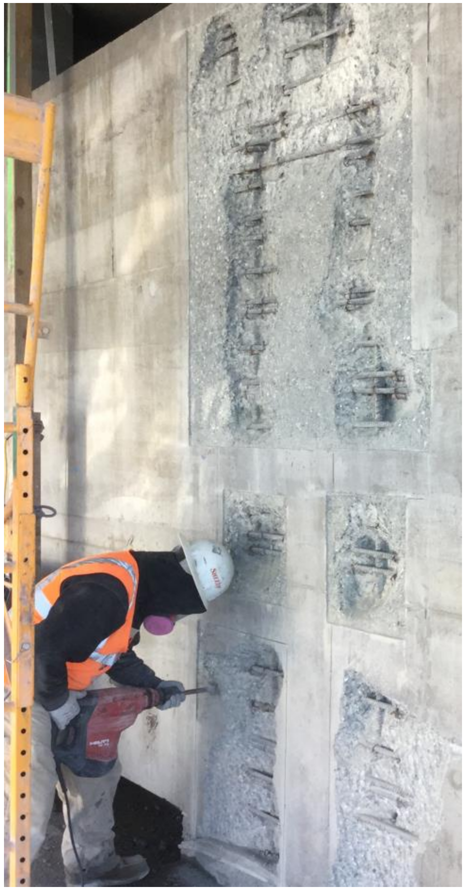

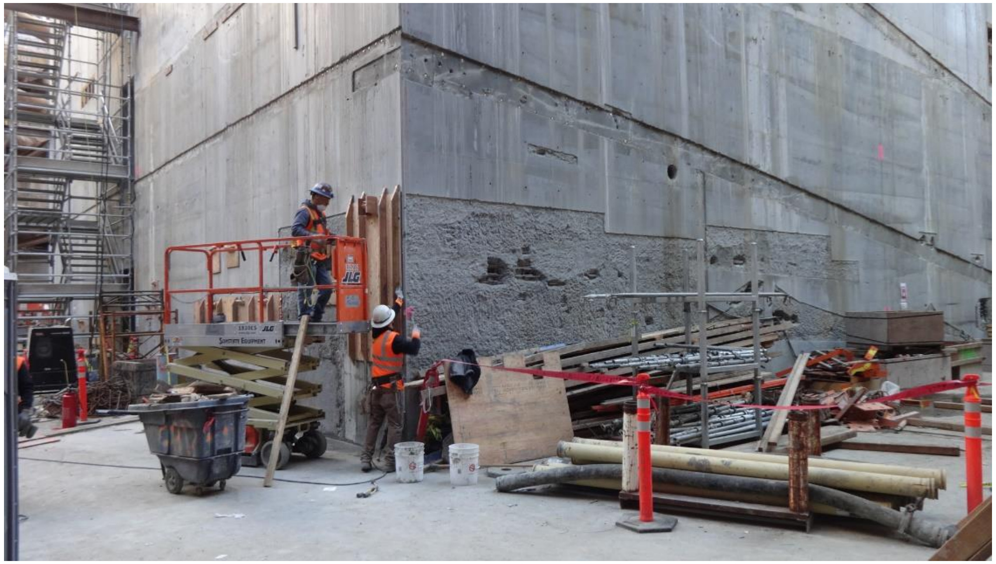
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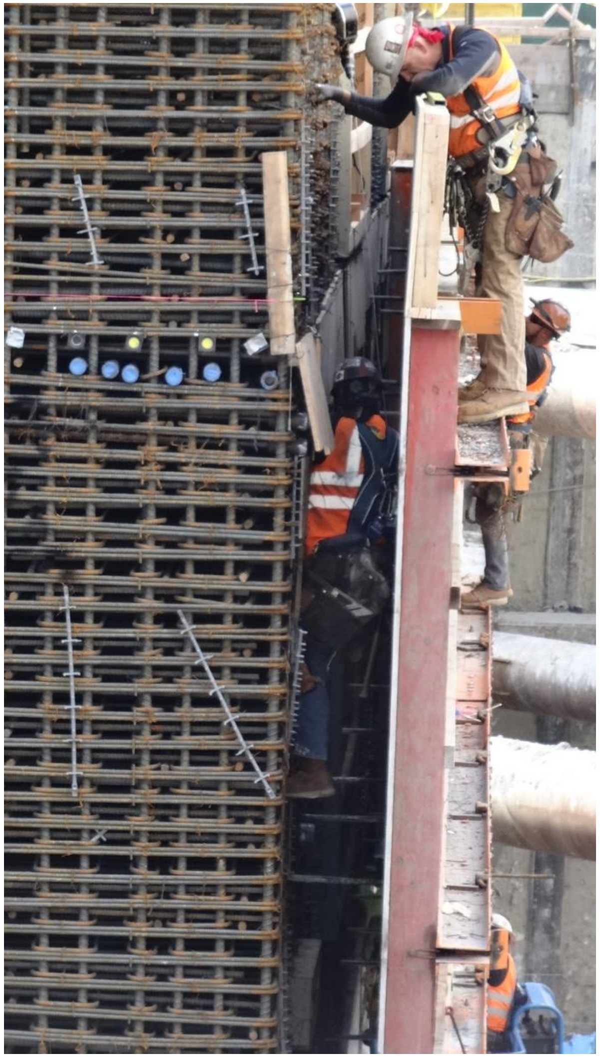


Congestion = Safety Hazards

Workers are at risk working through congested steel

Increases cost of work

Creates repair work

Adds rework

Current ACI 318-19 Commentary guidance for seismic design and Constructability

R18.2.2 *Analysis and proportioning of structural members*

In selecting member sizes for earthquake-resistant structures, it is important to consider constructibility problems related to congestion of reinforcement. The design should be such that all reinforcement can be assembled and placed in the proper location and that concrete can be cast and consolidated properly. Using the upper limits of permitted reinforcement ratios may lead to construction problems.

Design must consider constructability

Current ACI 318-19 Code requirements for reinforcing steel details (PT concrete end anchorage zones)

25.9.5 *Reinforcement detailing*

25.9.5.1 Selection of reinforcement size, spacing, cover, and other details for anchorage zones shall make allowances for tolerances on fabrication and placement of reinforcement; for the size of aggregate; and for adequate placement and consolidation of the concrete.

Design must consider tolerances of fabrication and placement.

CHAPTER 8—STRUCTURAL CONCRETE

8.1—Design and detailing prerequisites

In designing structural members and detailing formwork and reinforcement, consideration should be given to depositing the freshly mixed concrete as close as possible to its final position in such a way that segregation, honeycombing, and other surface and internal imperfections are minimized. Also, the method of consolidation should be carefully considered when detailing reinforcement and formwork. For example, for internal vibration, openings in the reinforcement should be provided to allow insertion of vibrators. Typically, 4 x 6 in. (100 x 150 mm) openings at 24 in. (600 mm) centers are required.

The designer should communicate with the constructor during the early structural design. Problem areas should be recognized in time to take appropriate remedial measures such as staggering splices, bundling reinforcing steel, modifying stirrup spacing, and increasing section size. When conditions contributing to substandard consolidation exist, one or more of the following actions should be taken: redesign the member; redesign the reinforcing steel; modify the mixture, in some cases to be self-consolidating; use mock-up tests to develop a procedure; and alert the constructor to critical conditions. The placing of concrete in congested areas is discussed in more detail in Chapter 18. Consideration should be given to using mechanical connections instead of overlapping the reinforcement to minimize congestion.

Design must consider access to provide proper consolidation

From ACI 309R-05

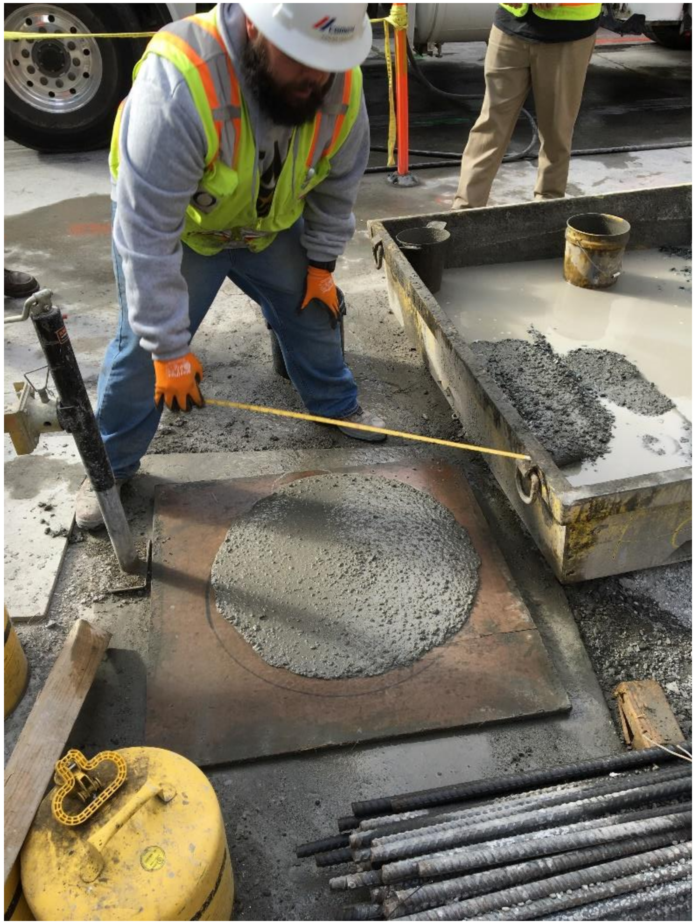
Attempt to outsmart congestion with slump

- 8 in. slump

- 26 in. spread (SCC)

Does higher slump or using SCC solves the problem?

Fig. 16 The end result of using flowing concrete, slump greater than 7 ½ in., on a 42 x 68 in. beam that was designed in accordance with ACI Code requirements. The four layers of #10 lap splices in the bottom of the beam prevented concrete flow and consolidation to reach the bottom.



For heavy congested rebar, SCC and high slump helps but the max aggregate size must be adjusted too

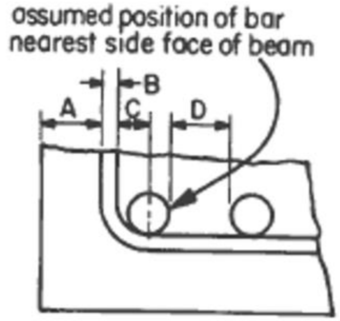
Add to Commentary section 25.9.5

- “To allow for tolerances on fabrication and placement of reinforcement, consider selecting: (a) the beam/girder at least 1 in. per ft (of beam/girder width) larger than the minimum required; or (b) the beam/girder at least 2 in. larger on each side than the intersecting column to allow outermost horizontal bars in the beam/girder to pass by the vertical longitudinal bars with minimal interference.”

Design must consider cross-section width and rebar congestion

Minimum beam width = $2(A + B + C) + (n - 1)(D + d_b)$ where $A + B + C - 1/2\, d_b \geq 2.0$ in. cover required for longitudinal bars and these assumptions are made:

for ACI 318



B = 0.375 in. for #3 stirrups
= 0.500 in. for #4 stirrups

D = $1\, d_b$
≥ 1 in.
≥ 1-1/3 nominal aggregate size

Fig. 5 This graphic provides the detailed explanation and equation used to determine the information provided in the design aid in Fig. 4. Note that the approach provided in these design aids, and typically used in current design software, do not account for any allowance for construction tolerance or adequate placement and consolidation of concrete. This often leads to a constructability issue for beams and girders.

The bar placement tolerance is ±1/2 in. when beam or girder depth is greater than 12 inches.

Adding these two tolerances to the minimum beam width equation yields:

$$Minimum\ beam\ width = 2(A + B + C) + (n - 1)(D + db)$$

$$+ fabrication\ tolerance + placement\ tolerance$$

Proposed equation to simplify minimum beam width:

(Account fabrication tolerance, ½ in. + placement tolerance, ½ in.):

Minimum beam width = 2(A+B+C) + (n-1)(D+db)

Constructable beam width = min width (1 + 1/12), rounded up to the nearest inch. This calculation adds 1 in. of width (per foot of beam width) to account for these tolerances.

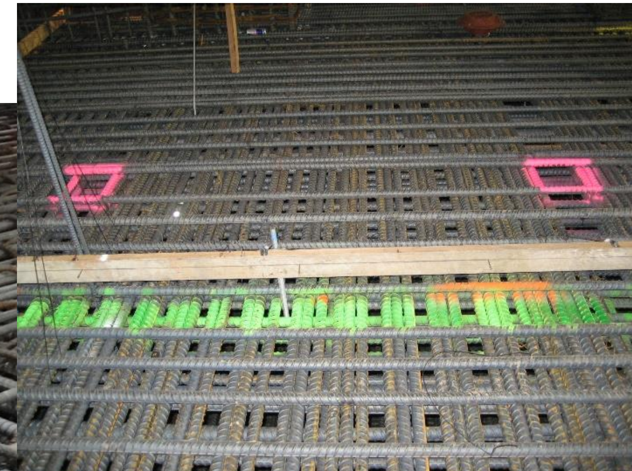
Consolidation by Vibration

Thanks to our colleagues in Committee 309...

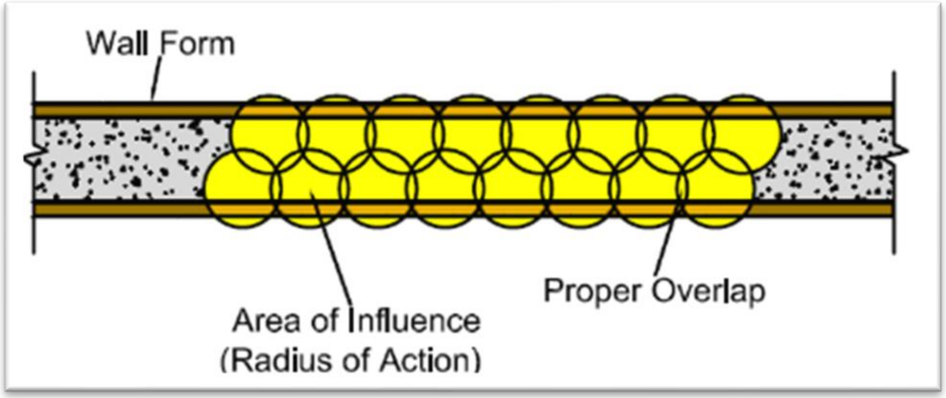
- ACI 309.1R-08: Report on Behavior of Fresh Concrete During Vibration
- ACI 309.2R-15: Guide to Identification and Control of Visible Surface Effects of Consolidation on Formed Concrete Surfaces
- ACI 309R-05: Guide for Consolidation of Concrete

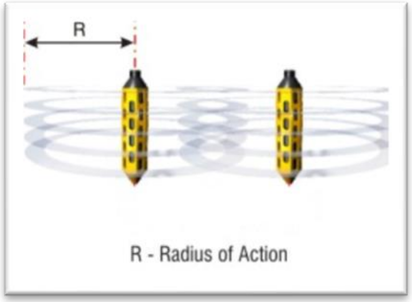
Add to Commentary section 25.9.5

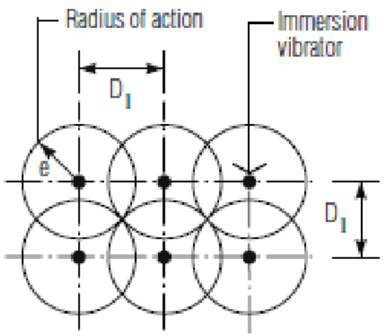
- “To allow for adequate consolidation of the concrete, consider providing access for a 5 in. diameter pump hose at regular spacings and designing a concrete mixture that is compatible with the concrete placement pump hose insertion spacing.”
- “A mockup may be necessary to evaluate this combination of parameters. The pump access spacing intervals should be shown in the construction documents.”



Access is important







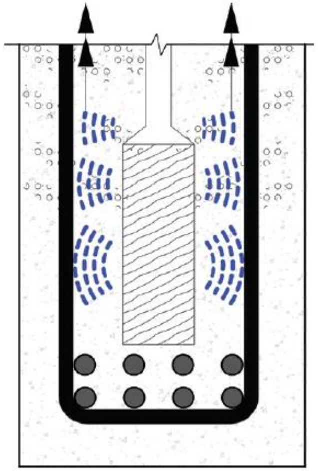
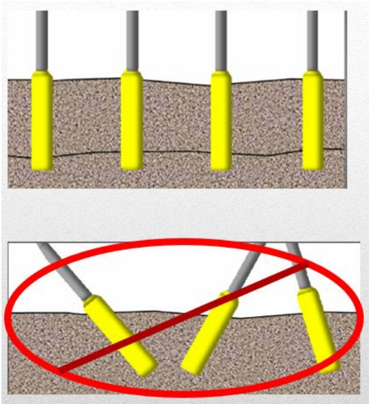


Fig. 6: An internal vibrator immersed in fresh concrete generates recurring circular compression waves. These waves consolidate the concrete and allow entrapped air to escape. Air pockets at the same level of the head or below tend to be trapped. Thus, the Wight and MacGregor[16] recommendation to provide enough space between beam bars to allow a vibrator to reach the bottom of the form is a necessary requirement if the concrete at the bottom of the beam is to be consolidated



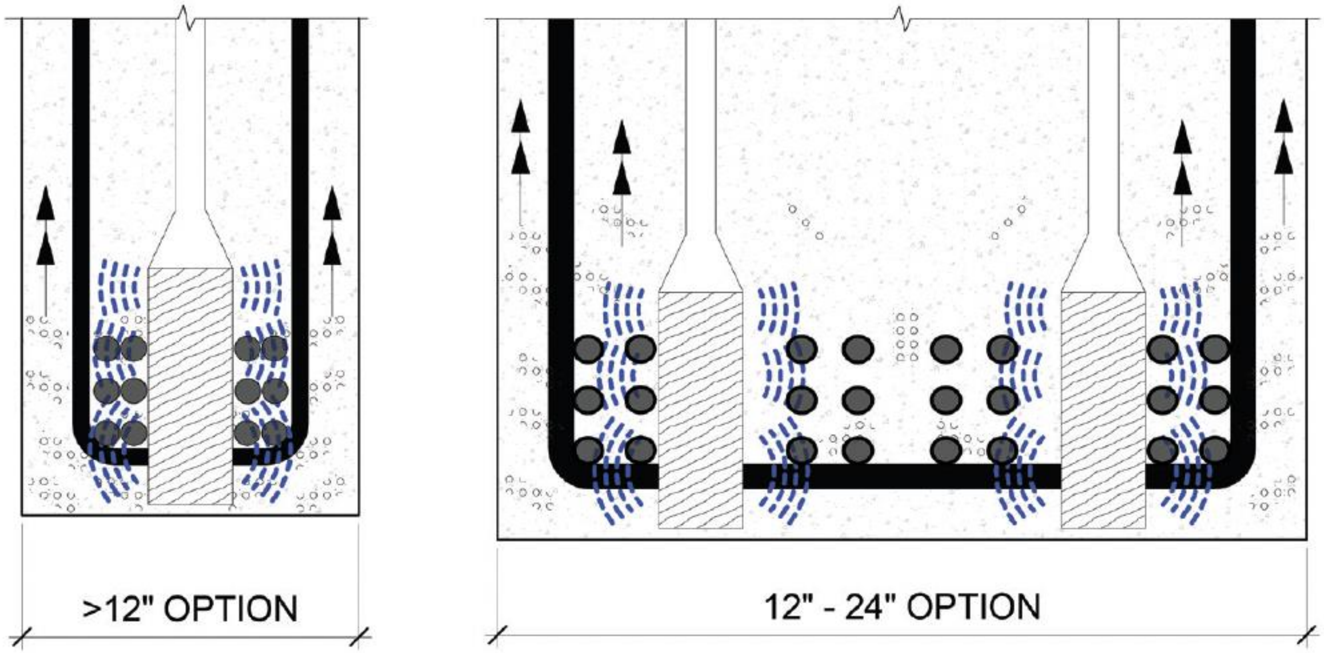


Fig. 7: Illustrates the recommendations for an allowance for adequate placement and consolidation for a beam less than 12 in. in width (one vibrator opening) and a beam from 12 to 24 in. in width (two vibrator openings). Note that this provides access for a 2-1/2 in. diameter vibrator head to reach the bottom of the beam to consolidate all the concrete

Design reinforcement with access to consolidation with vibration

Radius of Influence

Table 1:

Internal concrete vibrator radius of influence (distance from the center of the vibrator to the outer edge where complete consolidation takes place)

Head diameter, in.	Radius of influence, in.					
	ACI 309R-05	Manufacturer				
		A*	B	C	D	
3/4	3	3	5	—	5	
1-1/4	5	5	20	10	7	
1-1/2	6	6	24	14	13	
2	7	11	28	—	19	
2-1/2	10	13	32	16	24	
3	12	—	—	18	—	
3-1/2	14	—	48	—	—	

*Radius of influence can be twice the listed values when slump is high or HRWRAs are used

Access to Consolidation

Table 2:
Vibrator consolidation information based on ACI 309R-05

Vibrator head diameter, in	Radius of influence*, in.	Maximum insertion spacing, in.	Maximum beam width for one insertion in middle of beam, in.	Access space based on aggregate size, in.
3/4	3	4.5	4.0	1.00
1	4	6.0	5.5	1.33
1-1/4	5	7.5	6.5	1.66
1-1/2	6	9.0	8.0	2.00
1-3/4	7	10.5	9.5	2.33
2	8	12.0	10.5	2.66
2-1/4	9	13.5	12.0	2.99
2-1/2	10	15.0	13.5	3.33
2-3/4	11	16.5	14.5	3.66
3	12	18.0	16.0	3.99
3-1/4	13	19.5	17.0	4.32
3-1/2	14	21.0	18.5	4.66

*Depends on concrete slump

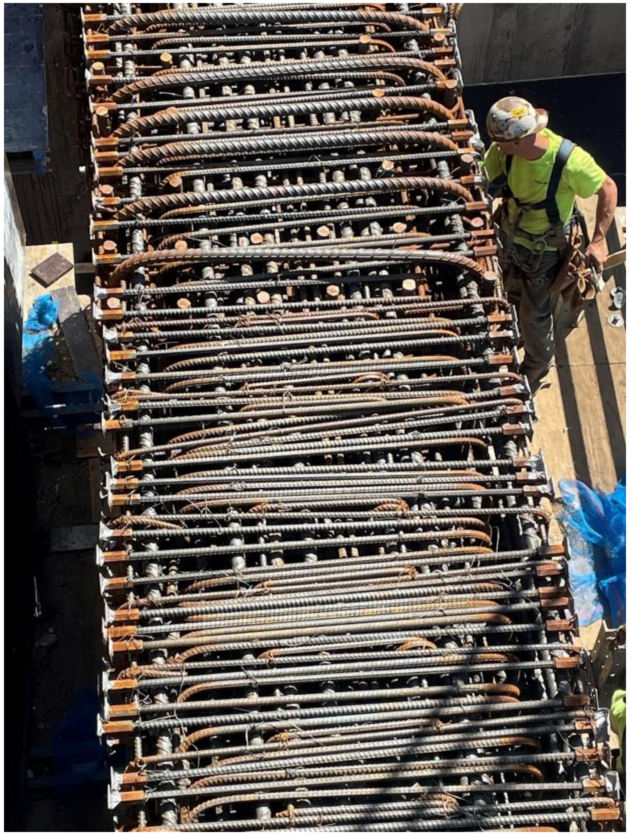
Vibration Insertions

Table 3:
Number of vibrator insertions for one concrete placement/lift

Number of vibrator insertions per 30 ft length*												
Vibrator head diameter, in.	Across	Beam/girder/wall width, in.										
		8	12	16	20	24	28	32	36	40	44	48
0.75	Width	2	3	4	5	6	7	8	9	10	11	12
	Length	80	80	80	80	80	80	80	80	80	80	80
	Total	**160**	**240**	**320**	**400**	**480**	**560**	**640**	**720**	**800**	**880**	**960**
1.25	Width	2	2	3	4	4	5	5	6	7	7	8
	Length	48	48	48	48	48	48	48	48	48	48	48
	Total	**96**	**96**	**144**	**192**	**192**	**240**	**240**	**288**	**336**	**336**	**384**
1.75	Width	1	2	2	3	3	3	4	4	5	5	6
	Length	35	35	35	35	35	35	35	35	35	35	35
	Total	**35**	**70**	**70**	**105**	**105**	**105**	**140**	**140**	**175**	**175**	**210**
2.25	Width	1	1	2	2	2	3	3	3	4	4	4
	Length	27	27	27	27	27	27	27	27	27	27	27
	Total	**27**	**27**	**54**	**54**	**54**	**81**	**81**	**81**	**108**	**108**	**108**
2.50	Width	1	1	2	2	2	3	3	3	3	4	4
	Length	24	24	24	24	24	24	24	24	24	24	24
	Total	**24**	**24**	**48**	**48**	**48**	**72**	**72**	**72**	**72**	**96**	**96**
2.75	Width	1	1	2	2	2	2	3	3	3	4	4
	Length	22	22	22	22	22	22	22	22	22	22	22
	Total	**22**	**22**	**44**	**44**	**44**	**44**	**66**	**66**	**66**	**88**	**88**

*Based on ACI 309R-05 radius of influence values and recommended vibrator insertion spacing of 1.5 x radius of influence

Add to Commentary section 25.9.5



"To allow for adequate consolidation of the concrete, consider providing a 4 in. square opening for an internal vibrator with a head diameter of 2 ½ in. to reach through to the bottom of the beam/girder for at least one location per 16 in. of beam/girder width and sufficient openings for internal vibration insertions at a maximum spacing of 16 in. on center along the length of the beam/girder."

Design reinforcement with access for vibration

Add to Commentary section 25.9.5

- "The structural drawings should show the placing sequence, especially the layering of beam-to-beam and beam-to-girder intersections, with consideration to intersecting beam and girder depths and concrete cover for each of the intersecting members."

- "Coordination of different design disciplines (e.g. electrical, mechanical, building skin) in the early schematic design phase is recommended to minimize congestion that would adversely affect reinforcement placement and concrete placement/consolidation."

IASMiRT

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Division XII

REINFORCEMENT IN CONSTRUCTION – HOW MUCH IS TOO MUCH!

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INTRODUCTION

We have reached a point in nuclear construction where the amount of reinforcement required in concrete is seriously threatening the viability of nuclear power plant (NPP) construction. Use of very dense cages (No. 11 or larger bundled within closely spaced ties/hairpins) with rebar densities of over 400 pounds per cubic yard of concrete are common. The current nuclear construction has experienced this issue and is faced with its serious implications on cost, schedule and the long-term performance of concrete.

This paper reviews the history of NPP design and construction for the extent of rebar and typical details used. Some of the major contributors leading to the current situation include the regulatory environment, Codes/Standards and the overreliance on the automated computer-based analysis and design process all of which results in many layers of conservatism.

The objective of this paper is to highlight the side effects of abusing the reinforcement especially its implications on construction process, project cost and schedule and possible performance. Suggestions are made to help reduce the layers of conservatism and improve the transparency of the design process through a "balanced" approach to accommodate the competing demands for reinforcement and constructability. Additional considerations including use of high-strength reinforcement and/or self-consolidating concrete and 3D rebar modeling are also discussed.

CONTRIBUTORS

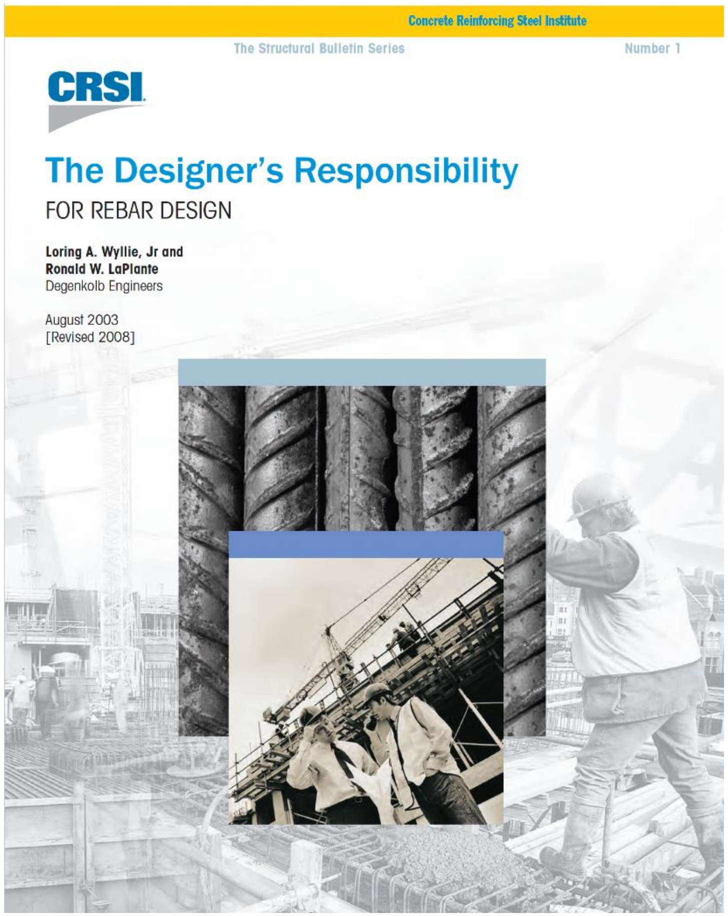
People

Human factors play a role in causing the rebar congestion issues. Since the last set of nuclear power plants in the United States were built more than 30 years ago, there is a significant talent and experience gap in the nuclear industry. Most of the engineers involved in the new designs are young and, thus, new to the industry. In absence of proper expert guidance and oversight and not having a clear understanding of structural behaviour and load paths, the human factors can lead to complex designs. In addition, the combined effect of lack of confidence and regulatory emphasis for extra safety, the designs often tend to be over conservative. Note that because the design process is generally separated from construction, it is not easy for this new generation of engineers to fully appreciate the downstream consequences of rebar congestion.

- Industry papers describes an epidemic of rebar congestion that is "*seriously threatening the viability of nuclear power plant (NPP) construction*."
- They recommend a rebar density value of 200 pounds per cubic yard (200 pcy) during schematic design to trigger "*early insight and course correction before it is too late.*"

Table 4 Rebar Density Early Design Review	
Concrete Element	Reinforcement Density (lbs./cy)
Beams/Girders	350/400
Columns	400
Footings, Spread	250
Foundations, Mat	300
Grade Beams	300
Slabs	200
Walls	300
Walls, Shear	400

- The 200 pcy threshold seems reasonable for standard elevated slabs, but it may still be low for other structural members. In many cases, it makes every member on the project subject to scrutiny.
- Based on industry experience, we chose trigger densities as shown in Table 4.


Concrete Reinforcing Steel Institute

The Structural Bulletin Series Number 1

CRSI

The Designer's Responsibility

FOR REBAR DESIGN

Loring A. Wyllie, Jr and
Ronald W. LaPlante
Degenkolb Engineers

August 2003
[Revised 2008]

Introduction

Many years ago, a contractor presented a structural engineer with a framed piece of plywood that had a #11 (#36) reinforcing bar bent into a 180° hook. The caption read: "This is a #11 bar, 1-7/16 inches in diameter. BE IT RESOLVED, I will never again hook #11 bars in an 8-inch wall." The momento was hung on the wall of the engineering firm to remind the engineers that designing for constructibility is an essential part of their job. An 8-inch thick wall with two curtains of typical wall reinforcement and several #11 (#36) bars with 180° hooks is a very congested situation.

As structural engineers, we have many responsibilities when designing a structure. We need to design members to resist the required loads and comply with the applicable building codes. In reinforced concrete members, we need to hook, develop and locate reinforcing bars so that they transfer forces properly and develop the required strength. We also need to detail the reinforcing bars so that they can be placed efficiently and with enough clearance that the concrete can be placed and consolidated properly. In other words, we need to size the members and design the reinforcement so that the structure can be built as designed.

Traditionally we are taught in our engineering classes to minimize the tonnage of reinforcing steel and cubic yards of concrete on the somewhat false premise that minimizing materials results in an economical design. In reality, labor is the most expensive item for construction in the U.S. When we "waste" a little concrete by making members larger so that the reinforcing steel can be placed more easily and the concrete consolidated more efficiently, we are actually achieving true cost savings.

The purpose of this paper is to highlight what we as designers can, and should, do in design and detailing to make reinforced concrete construction easier and thus more economical. The suggestions come both from the authors' own design experiences and their experience in peer reviewing the designs of other engineers. There is also a discussion of several details that are not always well understood by engineers. Although the focus is on issues related to earthquake-resistant construction on the West Coast, similar issues occur in reinforced concrete construction throughout the United States.

Conclusions

In this paper, the authors have offered some suggestions to their fellow structural engineers on our obligation to design and detail reinforced concrete structures so the contractor and reinforcing steel subcontractor can build them as easily and economically as possible. Most of these suggestions are common sense and simply require giving a little thought to how the design will be built. It has been the authors' experience that a well-detailed set of drawings, where these constructibility issues have been addressed, results in lower bid prices. Once you establish a reputation in this way, contractors will praise your drawings, consistently give your designs lower bid prices, and the word will spread, possibly bringing you new design commissions.