# Reinforcement Congestion in Cast-in-Place Concrete

## Allowances for construction tolerances and for adequate placement and consolidation

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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**

Concrete' reported by ACI Committee 309. (Presents current information on the mechanism of consolidation and gives recommendations on equipment characteristics and procedures for various classes of concrete.)"

That reference continues in ACI 318-19, Commentary Section R26.5.2.1(i), with minor changes in wording: "Detailed recommendations for consolidation of concrete are given in ACI 309R.[6] This guide presents information on the mechanism of consolidation and provides recommendations on equipment characteristics and procedures for various types of concrete mixtures."

The ACI 318 Commentary reference to ACI 309R-05[6] only considers depositing concrete—a contractor activity. It has never been referenced with respect to the selection or spacing of bars, although ACI 309R-05, Section 8.1—Design and detailing prerequisites, recommends reinforcement congestion issues be considered during early structural design.

ACI 309R-05, Section 8.1, also provides general design and detailing guidance:

"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 the insertion of vibrators. Typically, 4 x 6 in. (100 x 150 mm) openings at 24 in. (600 mm) centers are required."

That section further recommends that "special attention be directed to member size, reinforcing steel size, location, spacing, and other factors that influence the placing and consolidation of concrete. This is particularly true in structures designed for seismic loads where the reinforcement often becomes extremely congested and effective concrete consolidation, using conventional mixtures and procedures, becomes impossible."

Finally, ACI 309R-05, Section 8.1, recommends that the designer communicates with the contractor during early structural design, when problem areas can be recognized, in time to take appropriate remedial measures such as redesigning the member or reinforcing steel; modifying the mixture, in some cases to be self-consolidating; using mockup tests to develop a procedure; and alerting the contractor to critical conditions.

While Commentary Section R26.5.2.1(i) in ACI 318-19 instructs the engineer on issues that are to be communicated to the contractor in the construction documents, we believe that other sections of the Code Commentary should cite ACI 309R-05, thus instructing the engineer on issues that should be addressed in the design. For example, two additional appropriate locations for ACI 309R citations would be in R18.2.2 *Analysis and proportioning of structural members* and R25.9.5 *Reinforcement detailing.*

## Reinforcement Congestion Economics

When bidding on congested areas, reinforcement subcontractors indicate they reduce the overall productivity rate by 10 to 20%. When producing an estimate for a project, they assign productivity rates based on the reinforcement congestion. For example, the productivity rate for a heavily congested area could be half that of an uncongested area. Concrete contractors also decrease their productivity rates for concrete placement and consolidation in congested areas. In addition, the contractor must consider the risk and cost of patching honeycomb, which can be a big-ticket item.

Concrete costs increase if flowing concrete (a cost add of up to $\$20/yd^3$) or self-consolidating concrete (SCC) (a cost add of up to $\$75/yd^3$) is required to overcome reinforcement congestion. And the formwork cost may increase as well. ACI 237R-07(19), Self-Consolidating Concrete,[7] indicates that forms for SCC may need to resist high pressures (up to full-liquid head) and must be designed and constructed to be water-tight (both add to the costs of formwork).

Structural engineers generally strive to optimize the cost of structures, often by minimizing the sizes of structural members. Selecting minimum beam and girder widths based on current Code requirements decreases apparent costs by minimizing formwork area and the quantity of concrete. When minimized beam and girder widths lead to congested reinforcement, however, the final cost, including reinforcing bar installation, concrete placement, and consolidation, may actually increase. Even though Code requirements often refer to minimum or maximum values, Chapter 5 of ACI 315R-18, Guide to Presenting Reinforcing Steel Design Details, recommends: "Good design practice should generally strive to avoid the indiscriminate use of minimum code values without considering constructability."[8]

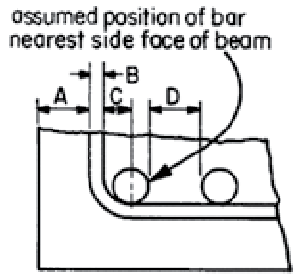
Malik mentions: "An emphasis on minimizing the size of concrete members, however, can lead to unintended consequences that may defeat the global goal of minimizing the construction cost for the overall project."[9] Malik further considers that concrete members sized purely on applied loads may not be large enough to accommodate the required amount of reinforcing steel with the proper spacing between bars. Conflicts can be created by the reinforcement for the member in question, reinforcing bars from adjacent members, and embedded anchor bolts or headed studs. These conflicts can potentially lead to honeycombs and voids in the concrete, inadequate cover, and inadequate embedment.

Honeycomb is expensive and can occur in any concrete element with congested reinforcement. Visible honeycomb typically leads to an investigation to determine if there are also interior voids. An investigation can cost from $10,000 to $50,000, and there is still the cost of repairing the honeycomb.

## Allowance for Reinforcement Fabrication and Placement Tolerances

The Concrete Reinforcing Steel Institute (CRSI) provides recommendations for choosing beam and girder widths to

Minimum beam width = $2(A + B + C) + (n - 1)(D + d_b)$ where $A + B + C - 1/2d_b \geq 2.0$ 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. 2: Because design aids such as this do not provide allowances for construction tolerances or requirements for adequate placement and consolidation of concrete, they can lead to honeycomb issues in beams and girders (from Table A-3 in Reference 11)**

allow for fabrication and placement tolerances: "The beam width determined from the maximum $M_u$ (largest factored bending moment) must be used for all spans; this will help in achieving economic formwork. Varying the amount of flexural reinforcement along the span lengths for different factored bending moments is far more economical than varying the beam width (or depth)."[10]

Also: "When selecting a beam width, it is important to consider the width of the columns at the ends of the beam. Greatest economy is achieved when the beam is as wide as or wider than the column: the formwork is much simpler where the beam is narrower than the column. Even though the formwork is simpler where the width of the beam is the same as the column, it is good practice to have a wider beam to avoid interference between the longitudinal corner bars of the beam and the column corner bars. It is recommended to have a beam width at least 4 in. wider than the column it frames into."[10]

The ACI Design Handbook[11] includes a table that provides the *minimum* beam or girder width to meet Code requirements based on the number and size of bars. Figure 2 shows the detailed explanation and equation used to determine the information provided in the table. Note that the approach provided in these design aids, and typically used in current design software, does not account for any allowance for construction tolerance or adequate placement and consolidation of concrete, nor does it allow for splices. These omissions can lead to constructability issues for beams and girders.

## ASCC Constructability Committee recommendations

The equation for the minimum calculated beam width in the design aid shown in Fig. 2 is:

Design aid beam width = $2(A + B + C) + (n - 1)(D + d_b)$

Where the variables are also defined in Fig. 2. The objective is to increase this minimum by a stirrup fabrication tolerance and bar placement tolerances. The stirrup fabrication tolerances are:

- ±1/2 in. for a No. 3, No. 4, or No. 5 stirrup with gross length < 12 ft;
- ±1 in. for a No. 3, No. 4, or No. 5 stirrup with gross length ≥12 ft; and
- ±1 in. for a No. 6 stirrup.

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

Constructable beam width = $2(A + B + C) + (n - 1)(D + d_b)$ + *fabrication tolerance* + *placement tolerance*

**Fig. 3: Pump hose and vibrator access zones (green paint) at the top of a congested shear wall. These zones were spaced 10 ft apart over the top of the wall and were continuous over the full height of the wall. The zones were coordinated in advance with the engineer and inspection agency**

The two tolerances can be treated separately or combined. There will be a fabrication tolerance for the enclosing stirrup, and a bar placement tolerance applied to the quantity of bars in a layer across the width of the beam.

The objective is to determine the minimum beam or girder width that ensures constructability. Rather than add the separate tolerances, the ASCC committee has also proposed using the following simplification:

Constructable beam width = design aid width (1+1/12), rounded up to the nearest inch.

For example, design aid beam widths of 9, 14, 24, and 42 in. would result in constructable beam widths of 10, 16, 26, and 46 in., respectively.

The allowances for fabrication and placement tolerances aren't necessarily added to the allowance for adequate concrete placement and consolidation of concrete. For instance, if SCC is specified with a flow greater than 24 in., an allowance for fabrication and placement tolerances is still needed even though an allowance for placement and consolidation isn't needed. If the proposed recommendations for allowance for placement and consolidation are used, however, the allowance for fabrication and placement may not be necessary. The engineer will need to decide on a case-by-case basis.

## Allowance for Adequate Concrete Placement

Although the Code requires the engineer to provide for adequate concrete placement, there is very little appropriate guidance in ACI documents for congested reinforcement. ACI 304R-00, Guide for Measuring, Mixing, Transporting, and Placing Concrete,[12] provides three recommendations that are typically not possible to satisfy when placing concrete through and around congested reinforcement:

1. Arrange equipment so that the concrete has an unrestricted vertical drop to the point of placement;
2. The stream of concrete should not be separated by falling freely over rods, spacers, reinforcement, or other embedded materials; and
3. Concrete should be deposited at or near its final position because it tends to segregate when it flows laterally into place.

ACI 304.2R-17, Guide to Placing Concrete by Pumping Methods,[13] doesn't provide additional information for adequate concrete placement.

Placement methods must be compatible with the concrete mixture. Some project specifications, unfortunately, do not require a concrete mixture that is compatible with the placement methods that are needed with congested reinforcement. This results in inconsistencies with concrete bids, honeycomb repairs, and changes in the concrete mixture.

### ASCC Constructability Committee recommendations

Placement and mixture recommendations that contractors have found beneficial for congested reinforcement include:

- Arrange reinforcement layout so a 5 in. pump hose can be lowered through the top reinforcement layer at 8 to 10 ft on-center (see Fig. 3 and 4). This may require temporary shifting of the top bars until after concrete has been placed over the bottom layers of reinforcement;
- Use portable placement chutes along the top of a wall (Fig. 5). Note, however, that the concrete stream will be deposited directly into reinforcement unless provisions are made for an opening in the vertical and horizontal reinforcement; and
- Develop a concrete mixture that:
  a. Flows laterally if it is impossible to deposit concrete in its final position. The concrete mixture must be designed to flow at least 10 to 15 ft laterally without segregation. This requirement is not only due to congested reinforcement and embedded items but also to blockouts and lap splices;
  b. Minimizes segregation when the concrete stream falls freely over rods, spacers, reinforcement, and other embedded items. Project mockups by ASCC contractors, and supported by the literature,[14] indicate no issues with directing the concrete stream through the reinforcement; and
  c. Minimizes segregation from free-fall. ACI 237R-07(19), Section 1.4, indicates that SCC has been used for free fall of about 15 ft without segregation.

A mockup might be necessary to prove the placement methods and concrete mixture compatibility with the degree of reinforcement. This should be included in the specifications and considered a bid item. ACI 237R-07(19), Section 2.4, indicates that the greater the amount of reinforcement and the more congested the form, the greater the potential for aggregate bridging and blocking that can lead to segregation of an SCC mixture. A smaller coarse aggregate size, usually 1/2 in., is used to minimize or eliminate possible bridging and blocking (also called aggregate straining in Europe) caused by congested reinforcement.[15] Even with a smaller coarse aggregate size, an SCC mixture must be sufficiently stable to reduce aggregate separation from the paste as the concrete flows between reinforcing bars.

A few project specifications provide concrete flow requirements. One such specification stated:

- Flowing concrete, 9 in. slump + 1 in., may be used to place concrete in walls with a uniform elevation, with a maximum lateral flow of 10 ft; and
- SCC may be placed at locations and allowed to flow up to 50 ft.

Conceptually, SCC should flow farther than flowing concrete; however, it's difficult to determine that distance prior to developing the concrete mixture and evaluating the percentage of reinforcement. ACI 237R-07(19), Section 6.5.3, indicates that the maximum allowable horizontal spread distance for an SCC mixture used in a slab will depend on the stability of the concrete and is typically limited to 33 ft. For congested reinforcement, without a mockup, it would be prudent to consider 20 ft as a practical maximum flow distance to minimize aggregate straining.

Fig. 4: Concrete pump hose access zones (pink paint). These zones were 6 in. square and were spaced 8 to 10 ft apart. Typically, top bars in both layers were shifted into proper design position and secured after pumping of the lower mat was complete. Temporary shifting of top layer reinforcing was coordinated in advance with the engineer and inspection agency

Fig. 5: Portable concrete placement chute, 16 in. wide by 12 in. deep, used at the top of the wall to allow SCC to be placed through the side of congested shear wall. Several jobsite-built wood chutes were leapfrogged to keep in front of the placing crew. Preconstruction mockup cores taken through reinforcing steel at the bottom of congested boundary elements indicated no aggregate separation

## Allowance for Adequate Concrete Consolidation

Recommendations for reinforcement detailing to allow for adequate consolidation have been provided by CRSI,[10] ACI 309R-05, Wight and MacGregor,[16] and Roberts.[17] Although these recommendations have existed for some time, they are not currently being implemented. The recommendations include:

- **CRSI**: "Provide a 4 to 6-inch gap to place concrete where bars are closely spaced. In heavily reinforced members, such as transfer girders, where the spacing between bars is relatively close, provide a gap of 4 to 6 in. between bars, if possible. Based on experience, a 4-inch slump concrete with 3/4-inch aggregate will not flow easily through a 2-inch space between bars. Also, vibrator heads, which are usually 2 to 3 in. in width, may not fit between the bars or can become entangled in the bars if the space between bars is too small."[10]
- **ACI 309R-05, Section 18.2.1**: "To achieve proper concrete consolidation in congested areas by internal vibration, obstruction-free vertical runs of 4 x 6 in. (100 x 150 mm) minimum cross section are needed to permit vibrator insertion. The horizontal spacing of these vertical runs should not exceed 24 in. (610 mm) or 1-1/2 times the radius of influence indicated in Table 5.1. Also, these openings should not be more than 12 in. (300 mm) or 3/4 times the radius of influence from the form. If such runs cannot be provided without compromising structural integrity, the engineer should specify construction details and procedures to achieve proper consolidation."
- **Wight and MacGregor**: "The arrangement of bars within a beam must allow sufficient concrete on all sides of each bar to transfer forces into and out of the bars; sufficient space so that the fresh concrete can be placed and consolidated around all the bars; and sufficient space to allow an internal vibrator to reach through to the bottom of the beam. Pencil-type concrete immersion vibrators used in consolidation of the fresh concrete are 1-1/2 to 2-1/2 in. in diameter. Enough space should be provided between the beam bars to allow a vibrator to reach the bottom of the form in at least one place in the beam width."[16]
- **Roberts**: "Where it is believed that the reinforcement is congested, i.e., at a beam/beam junction, CAD systems can be used to produce 3D illustrations of the congested area. Check the illustration to see if a 75 mm (3 in.) or 50 mm (2 in.) diameter poker vibrator can pass through the congested reinforcement. Allow for the fact in this exercise that bars vertically above each other will be slightly displaced in plan."[17]

While all references recommend a consolidation opening, Wight and MacGregor[16] offer a key emphasis—provide an opening to allow the vibrator to reach the bottom of the placement. ACI 309R-05, Section 7.2, provides the rationale for this recommendation: "The vibrator exerts forces outward from the shaft. Air pockets at the same level at or below the head tend to be trapped." As previously stated, ACI 309R-05, Section 18.2.1, indicates the preferred space for consolidation—4 x 6 in. minimum cross section with the horizontal spacing of these openings not to exceed 24 in.

The implication of this recommendation is not obvious. Based on the ACI 309R-05 recommended insertion spacing of 1.5 times the radius of influence and the radius of influence as provided in Table 5.1 in the document, the minimum vibrator head diameter to allow horizontal spacing at 24 in. on-center would be approximately 5 in. Most contractors are not using a 5 in. diameter vibrator head. A more practical choice is a 2-1/2 in. vibrator head (see the Selecting a Vibrator section), which then translates to openings approximately 16 in. on-center.

ACI 309R-05, Section 18.2.1, requires the maximum aggregate size to be 3/4 of the clear spacing between bars. Therefore, for a 1 in. clear spacing, the maximum aggregate size would be 3/4 in. For multiple layers of bars, the aggregate can snake between bars that are not placed directly above each other. As Roberts noted,[17] bars placed within tolerance, may not be "directly" above each other. Internal vibrator head length varies from about 6 to 9 in. for short-heads and 12 to 16 in. for regular heads. The rigid vibrator heads will not be able to follow the same tortuous path of an aggregate particle as it snakes through the openings between bars. If the aggregate needs 3/4 of the clear spacing, the vibrator head diameter should be the same or less, perhaps 1/2 of the clear opening. Based on the Code requirements on the clear space between bars, this would limit the vibrator head size to 3/4 in. or less to "tickle" the aggregate in the concrete. Clearly, that is not effective consolidation.

### ASCC Constructability Committee recommendations

The following recommendations are proposed for appropriate allowances for adequate consolidation of the concrete unless no consolidation is specified or required:

- Openings must allow the vibrator to reach the bottom of the beam or girder (Fig. 6);
- Based on a minimum 2-1/2 in. diameter vibrator head, there must be one opening per 16 in. of beam or girder width (Fig. 7); and
- The opening size must be a minimum of 16 in.$^2$ (4 x 4 in.) with spacing at 16 in. on-center.

### Selecting Vibrator Size

For speed and ease of consolidation, the contractor selects the largest diameter head feasible for the project. Based on higher amplitude vibration, larger heads have a larger radius of influence; therefore, requiring fewer vibrator insertions at greater interval spacing to achieve proper consolidation. Fewer insertions result in faster working times. Areas of reinforcement congestion, however, limit the diameter of the vibrator head that can be inserted between the specified reinforcement clear spacing. Additionally, allowable fabrication and placement tolerances may reduce the clear spacing below that specified.

As mentioned, the radius of influence is an important factor in selecting vibrator head diameter. Table 1 provides the radius of influence from ACI 309R-05 and values listed by four vibrator manufacturers. Based on experience, the values listed in ACI 309R-05 appear to be conservative, perhaps based on a low-slump concrete. The values listed by the manufacturers are as much as four times that of the ACI 309R-05 values and may not be appropriate.

Based on the information provided in ACI 309R-05 for different diameter vibrator heads, Table 2 includes the radius of influence, maximum insertion spacing, maximum beam width for one vibrator insertion in the middle, and vibrator access space limited to 3/4 in. clear spacing.

Table 3 provides the number of vibration insertions per beam width for a 30 ft beam, girder, or wall length, based on vibrator size. As an example, consider a width of 24 in., but where only a 3/4 in. vibrator head can be used due to reinforcement detailing. The 3/4 in. vibrator would need to be inserted six times across the width and 80 times across a 30 ft length for a total of 480 insertions. A more realistic option may be to use a 2-1/2 in. diameter head resulting in 54 insertions to cover 30 ft of the 24 in. width. However, the option of using the 2-1/2 in. head can only be considered if reinforcement detailing can accommodate at least a 3-1/2 in.$^2$ access space at about 16 in. lateral spacing. Note that this is vibrator insertions per lift. If the beam/girder/

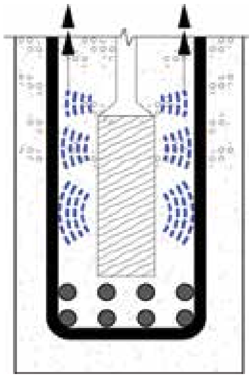


**Fig. 6: An internal vibrator immersed in fresh concrete generates recurring circular compression waves. These waves consolidate the concrete and allow entrapped air to escape. Air pockets at the same level of the head or below tend to be trapped. Thus, the Wight and MacGregor[16] recommendation to 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**

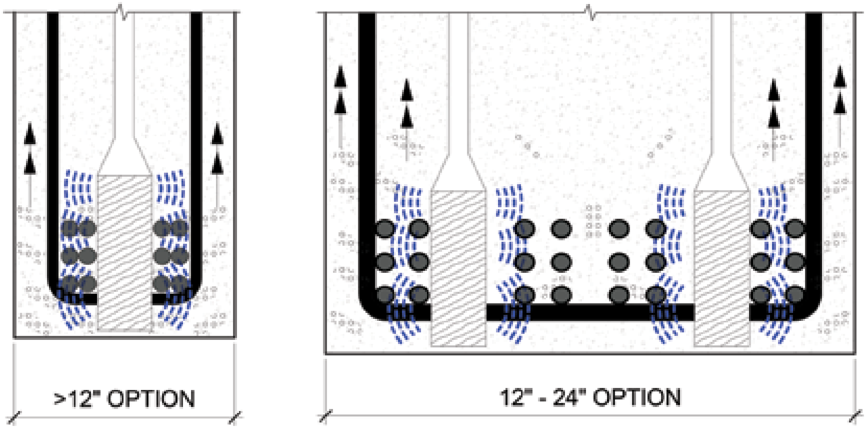



**Fig. 7: Illustrates the recommendations for an allowance for adequate placement and consolidation for a beam less than 12 in. in width (one vibrator opening) and a beam from 12 to 24 in. in width (two vibrator openings). Note that this provides access for a 2-1/2 in. diameter vibrator head to reach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

wall requires more than one lift, the number of vibrator insertions for that element must be multiplied by the number of lifts.

### ASCC Constructability Committee recommendations

If concrete requires consolidation, the engineer, during design, should consider a 2-1/2 in. diameter head as the minimum vibrator size. Smaller vibrators can be used to supplement larger vibrators, but the smaller vibrators should not be considered typical use.

## Concrete Mixture Considerations

Changes to the concrete mixture to account for areas with congested reinforcement were provided in the 1941 ACI Building Code, Section 404 (d): "Where conditions make compacting difficult, or where the reinforcement is congested, batches of mortar containing the same proportions of cement to sand as used in the concrete, shall first be deposited in the forms to a depth of at least one inch."[18] In this Code, the minimum clear distance between parallel bars was 1-1/2 times the diameter for round bars and twice the side dimension for square bars. And the maximum size aggregate could be no larger than 3/4 of the minimum clear spacing between reinforcing bars.

The provision for using the mortar batches where reinforcement is congested continued through the 1947, 1951, 1956, 1963, and into the 1971 Code. It was removed from the 1977 Code, as the Commentary Section 5.4 stated: "That requirement was deleted from the 1977 code since the conditions for which it was applicable could not be defined precisely enough to justify its inclusion as a code requirement. The practice, however, has merit and should be incorporated in job specifications where appropriate, with the specific enforcement the responsibility of the job inspector. The use of mortar batches aids in preventing honeycomb and poor bonding of the concrete with the reinforcement."[19]

CRSI[10] recommends the use of high-performance concrete where placement and consolidation are expected to be difficult. High-performance concrete is defined as meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices. These requirements could potentially increase the ease of placement and consolidation.

ACI 309R-05, Section 18.2, recommends that consolidation in congested areas can be improved by increasing flowability of the mixture using chemical admixtures. Chemical admixtures such as high-range water-reducing admixtures (HRWRAs) provide high slump flowing concrete without altering the selected water-cementitious materials ratio (*w/cm*). Section 18.2.2 indicates that the use of chemical admixtures does not, however, replace the requirement for good consolidation by vibration.

ACI 212.3R-16[20] provides information on flowing concrete (Chapter 17) and SCC (Chapter 18), specified on some projects with reinforcement congestion. This is a consideration when deciding on allowances for fabrication

### 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

### 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

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

| Vibrator head diameter, in. | Across | Number of vibrator insertions per 30 ft length* — 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

and placement tolerances and concrete placement and consolidation. The use of flowing concrete or SCC might minimize the effect of congestion but does not guarantee the absence of honeycomb.

For SCC, the slump flow value allows the comparison of the lateral flow and filling potential of different mixtures. A common range of slump flow for SCC is 18 to 30 in. (450 to 760 mm). The higher the slump flow, the farther the SCC can travel under its own mass from a given discharge point, and the faster it can fill a form. For congested reinforcement, the ASCC Constructability Committee recommends a slump flow value greater than 26 in. with a maximum coarse aggregate size of 1/2 in.

ACI 237R-07(19), Section 1.1, defines SCC as a highly flowable, nonsegregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without mechanical vibration. Some project specifications require no consolidation for SCC—which tells contractors not to put a cost on this item. This direction, however, needs to be carefully examined for SCC in highly congested reinforcement. ACI 237R-07(19), Table 2.5, does recommend consolidation for a high level of reinforcement and SCC with a slump flow lower than 22 in. (550 mm). Batch-to-batch variability of slump flow might also present a need to consolidate the concrete. The desire for internal vibration of SCC, however, is dependent on the reinforcement congestion.

High-strength SCC is often used in the vertical elements. This mixture usually consists of low *w/cm* of 0.23 to 0.35, high cementitious contents (from 700 to 1000 lb/yd$^3$), one or more supplementary cementitious materials (fly ash, slag cement, or silica fume), smaller coarse aggregate sizes (1/2 in. maximum), a viscosity modifying admixture, and high dosages of HRWRAs (typical retarding). This mixture, in thick walls or mat foundations, could create a thermal issue and must be recognized in the design phase, especially if internal cooling pipes are necessary. If they are, they will only add to the congestion issue. Furthermore, this mixture will also create additional constructability issues if it needs to be puddled in the surrounding slabs.

## Embedment and Penetrations

In addition to reinforcement, embedments such as weld plates with studs, anchor bolts, and structural steel members, and MEP penetrations also add to the congestion. Schafer states that the engineer needs "to coordinate our drawings and design with other disciplines,"[21] including the mechanical and electrical requirements. When coordination does not take place during the design phase, congestion can occur. Coordination of different disciplines' work is necessary during the design phase, or extra cost and schedule delays will occur at construction.

## Reinforcement Density to Trigger Early Design Review

Munshi and Saini[22] concluded that nuclear construction has reached a point where the amount of reinforcement required can seriously threaten the viability of power plant construction. They indicated that very dense cages (No. 11 or larger bundled within closely spaced ties/hairpins) with reinforcing bar densities of over 400 lb/yd$^3$ of concrete were common. And that current nuclear construction has experienced this issue and is faced with serious implications on cost, schedule, and long-term performance of the concrete.

Certainly, reinforcement required in building construction, especially for seismic design, has also reached a critical level. Reinforcing bar densities for mat foundations are approaching 600 lb/yd$^3$ and walls are 700 to 800 lb/yd$^3$ (Fig. 8). One wall in a nonseismic region is close to 1000 lb/yd$^3$ of reinforcement. When determined in the field, these levels of bar density require contractors to work with the engineer to redesign the reinforcement layout, resulting in extra cost and delays.

Munshi and Saini proposed that bar density be used as an early trigger review:

"To facilitate early insight and course correction before it is too late, it is advisable to include a detailed review of the design developments in early stages of design to ensure that the design criteria, assumptions, processes, and methods are yielding reasonable design and reinforcement. A review of the rebar densities should be carried out at this early stage to help identify potential areas of high rebar densities that need to be critically evaluated to understand the root cause and corrected in time before the design is finalized. As a matter of general rule of thumb, rebar densities exceeding 200 lb/yd$^3$ can be used as a trigger point to evaluate the designs at early stages."[22]

It is unclear why Munshi and Saini[22] chose 200 lb/yd$^3$ as a trigger point to evaluate designs. For some building construction, this limit might result in a congestion review of every member. Based on our experience, the ASCC Constructability Committee chose to identify trigger reinforcement densities by element, as shown in Table 4.

## Proposed Code and Commentary Provisions

The ASCC Constructability Committee is proposing ACI 318 Code and Commentary provisions related to constructability with respect to reinforcement congestion. These proposed changes, especially in a design-bid-build delivery system, should resolve congestion issues, thus avoiding countless requests for information (RFIs).

Proposed ACI 318 Code and Commentary provisions to improve constructability include:

### Code

*Reinforcement detailing*

Selection of reinforcement size, spacing, cover, and other details 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.

### Commentary

*Reinforcement detailing*

Code requirements often refer to minimum or maximum values. Good design practice (ACI 315) generally strives to avoid the indiscriminate use of minimum Code values without considering constructability. Constructability is an important part of providing the owner with a structure within cost, schedule, and quality constraints.

To allow for tolerances on fabrication and placement of reinforcement, consider selecting: (a) the beam/girder at least

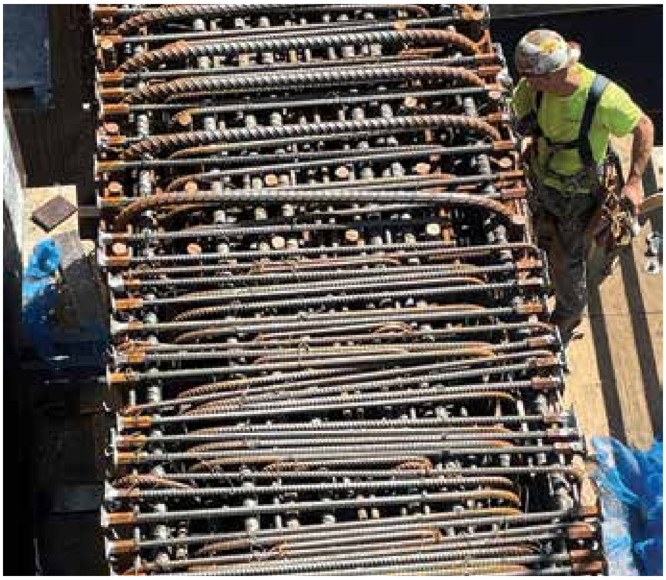


**Fig. 8: Reinforcing bar density for this member was close to 800 lb/yd$^3$. After this was built, the engineer changed bar sizes, bundled bars, and rearranged splices so there was access for concrete placement**

### Table 4:
**Reinforcement densities trigger points by element**

| Concrete element | Reinforcement density, lb/yd$^3$ |
|---|---|
| Beams/girders | 350/400 |
| Columns | 400 |
| Footings, spread | 250 |
| Foundations, mat | 300 |
| Grade beams | 300 |
| Slabs | 200 |
| Walls | 300 |
| Walls, shear | 400 |

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.[10]

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 insertion spacing. A mockup may be necessary to evaluate this combination of parameters. The pump access intervals should be shown in the construction documents.

To allow for adequate consolidation of the concrete, consider providing a 4 in. square opening for an internal vibrator with a head diameter of 2-1/2 in. to reach through to the bottom of the beam/girder[16] 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.[6,10]

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.[8]

Coordination of different design disciplines in the early design phase is recommended[21] to minimize congestion that would adversely affect reinforcement and concrete placement and consolidation.

## Commentary References

ACI 309R-05—Guide for Consolidation of Concrete

ACI 315-18—Guide to Presenting Reinforcing Steel Design Details

CRSI 10-DG-STRUCTURES —Design Guide for Economical Reinforced Concrete Structures, 2016

Schaefer, S.E., "Coordinated and Complete Construction Documents—CASE's Answer to 'Botched Plans'," *STRUCTURE* magazine, Feb. 2004, pp. 27-29.

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## The Designer's Responsibility

Wyllie and LaPlante[23] offer suggestions to other structural engineers on their obligation to design and detail reinforced concrete structures so the contractor and reinforcing steel subcontractor can build them as easily and economically as possible. The authors state that it has been their experience that a well-detailed set of drawings, where constructability issues have been addressed, results in lower bid prices.

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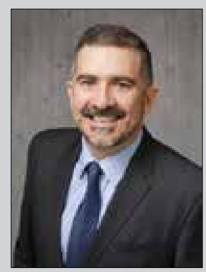

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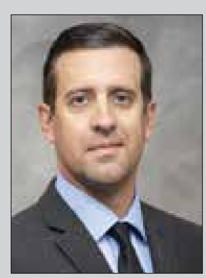

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