Updated 5/21/2025

Constructability BLUEPRINT

PRO™

An ACI Center of Excellence for Advancing Productivity

www.concreteproductivity.org

PRO PROUDLY RECOGNIZES

Founding Member: aci American Concrete Institute

Members: BAKER Construction, CKC Structural Engineers, Wayne Brothers Companies, CECO, The Conco Companies, Somero Enterprises, Inc., CEMEX, CFA, PS=0, ASCC

PRO: An ACI Center of Excellence for Advancing Productivity was established in 2023 by the American Concrete Institute. Its purpose is to be a catalyst for solving the barriers of constructability to advance concrete construction productivity, leveraging ACI's role as a world-leading authority for the development, dissemination, and adoption of consensus-based standards for concrete design, construction, and materials.

TABLE OF CONTENTS

PRO MEMBERS

PLATINUM

BAKER Construction

+1.800.539.2224
https://bakerconstruction.com/

GOLD

CKC Structural Engineers

+1.425.455.2144
https://www.ckcps.com/

Wayne Brothers Companies

+1.704.956.2200
https://waynebrothers.com/

SILVER

CECO

+1.816.459.7000
https://cecoconcrete.com/

The Conco Companies

+1.925.685.6799
https://www.conconow.com/

Somero Enterprises, Inc

+1.239.210.6519
https://www.somero.com/

BRONZE

CEMEX

+1.713.650.6200
https://www.cemexusa.com/

CFA Concrete Frame Associates

+1.303.341.5035
https://www.concreteframe.com/

PS=0

+800.355.8414
https://pourstrip0.com/

AFFILIATED

ASCC

+1.866.788.2722
https://ascconline.org/

PRO
An ACI Center of Excellence for Advancing Productivity

Constructability BLUEPRINT

SECTION 1: VALUE OF DESIGN COLLABORATION

1.1 WHAT IS CONSTRUCTABILITY?

PRO defines constructability as the effective integration of construction knowledge into the planning and design of a project to optimize its construction cost and schedule and maximize its value to the owner.

Constructability practices should be introduced as early as possible to achieve the best results, potentially providing a 10:1 return on the owner's investment, according to the **Construction Industry Institute (CII) Task Force**. Constructability input during design will improve efficiency once construction begins, reducing requests for information (RFIs), redesigns, and overall construction time.

Concrete constructability is not about sacrificing architectural creativity or owners' goals. On the contrary, it helps achieve desired architectural and ownership outcomes by reducing the complexity, leveraging local labor and materials, maximizing the productivity potential of concrete construction systems, and capitalizing on available technologies. In short, constructability improves construction productivity through effective designer/contractor collaboration.

The CII **Constructability Graph** (Fig. 1.1.1) illustrates stages in the design and construction process and ability to influence final project costs. As can be seen, the greatest potential for cost reduction arises during the conceptual planning and early design stages. At these stages, designer/concrete contractor collaboration can pay big dividends.

A key element of improving concrete constructability is to create fully complete and coordinated structural concrete design documents. A poll of members of the American Society of Concrete Contractors (**ASCC**) showed that 75% of ASCC members believe that poor design documents are the single largest barrier to improving field productivity. Time and labor efficiencies are lost when the design information is inferior, insufficient, and/or inaccurate.

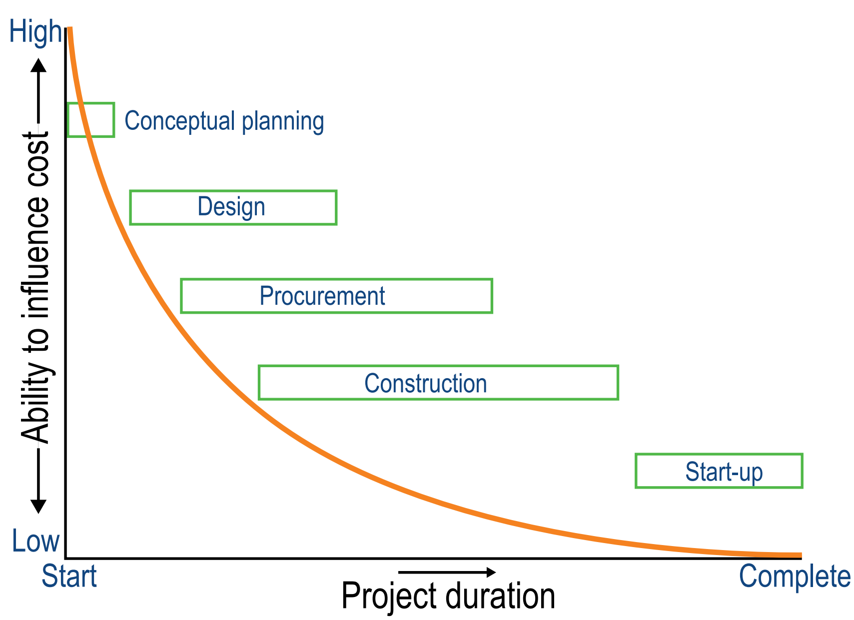


Fig. 1.1.1: The ability to influence the final cost of a project decreases rapidly with each phase of the project ("Constructability: A Primer, Construction Industry Institute," Austin, TX, 1986, 24 pp.)

1.2 IMPROVING PRODUCTIVITY VIA CONSTRUCTABILITY

According to the Construction Industry Institute Task Force, effective constructability programs can lower project costs (4.3% reductions on average) and shorten project timelines (7.5% reductions on average) while minimizing rework, improving safety, and advancing environmental sustainability.

Constructable designs capitalize on the available construction personnel and skills, materials, and equipment while accounting for other factors such as local weather and general construction logistics. Constructable designs also have fully complete and coordinated structural design documents that are dimensionally compatible with architectural and other design professionals' plans, and that apply appropriate construction tolerances selected to reduce rework and avoid conflicts with trades that follow the structural work.

Concrete specifications that are performance based rather than prescriptive can set the stage for innovative construction solutions. For example, properly specified performance-based concrete mixture designs will empower the concrete contractor and concrete supplier to achieve desired strength, durability, and embodied carbon goals in efficient and innovative ways.

Standardizing element sizes and concrete mixtures, and reducing reinforcement congestion early in the design process, improves constructability by reducing construction complexity. When constructability is improved, shop and field labor can achieve higher levels of productivity while time of construction is reduced.

Miami World Tower. (Image courtesy of Ceco Concrete Construction.)

1.3 STATUS OF CONSTRUCTION PRODUCTIVITY

According to studies conducted by the McKinsey Global Institute (MGI) and others, construction productivity was essentially stagnant from 1947 to 2010 (refer to Fig. 1.3.1). During that same period, however, productivity gains in manufacturing, retail, and agriculture ranged from 800 to 1600%. This trend is unacceptable, as construction contributes 4% of the U.S. gross domestic product (GDP).[1] To ensure society is able to continue to afford efficient and safe infrastructure and buildings, construction productivity must increase.

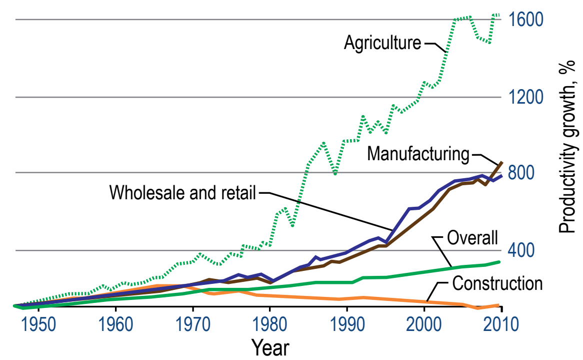


Fig. 1.3.1: For decades, construction productivity has experienced little or no growth, while other sectors have experienced massive gains in productivity. (Barbosa, F. et al., "Reinventing Construction: A Route to Higher Productivity," McKinsey Global Institute, Feb. 2017, 158 pp.)

A recent study published by the National Bureau of Economic Research further shows that construction prices over the past 70+ years have skyrocketed in comparison to the GDP. As demonstrated in Fig. 1.3.2, construction cost increases have been most dramatically affected by poor labor productivity, as the cost of construction intermediates (energy, materials, and purchased services) have tracked with the GDP over the same period.

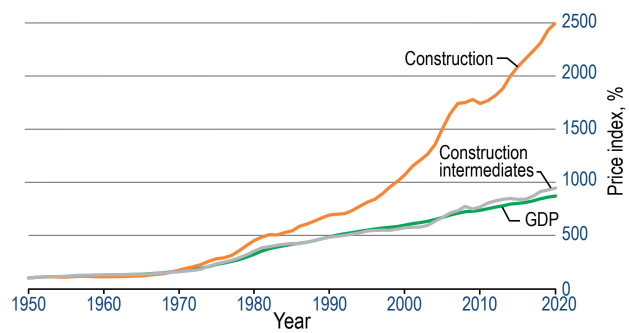


Fig. 1.3.2: Price indexes for construction, construction intermediates, and GDP, from 1950 to 2020. (Goolsbee, A., and Syverson, C., "The Strange and Awful Path of Productivity in the U.S. Construction Sector, Working Paper 30845," National Bureau of Economic Research, Jan. 2023, Revised Feb. 2023, 27 pp., http://www.nber.org/papers/w30845)

PRO members have expressed concerns that insufficient collaboration between designers and contractors is the source of this poor performance, as it leads to designs lacking in constructability. As architectural and structural designs have become increasingly complex, time constraints can force constructability considerations to take a back seat. The resulting construction documents may lack adequate coordination, so construction productivity suffers.

The previously cited MGI report observed that acting in seven areas simultaneously could boost construction productivity by 50 to 60%. The cited enablers are:

- Reshaping regulation and raising transparency;
- Rewiring the contractual framework to reshape industry dynamics;
- Rethinking design and engineering processes;
- Improving procurement and supply chain management;

[1]Johnson, A., "Using Construction as an Economic Indicator," *Forbes*, Aug. 6, 2023 (https://www.forbes.com/sites/forbesbusinesscouncil/2023/08/16/using-construction-as-an-economic-indicator/?sh=63ca20467bfa)

- Improving on-site execution;
- Infusing digital technology, new materials, and advanced automation; and
- Reskilling the workforce

In response to this industry challenge, the American Concrete Institute (ACI) decided to tackle the issue of productivity in concrete construction. A small group addressed McKinsey's findings and recommendations at an ACI Foundation Strategic Development Council (SDC) meeting in 2020, and the group's insights led to the formation of an ACI Board Task Group that developed recommendations for how ACI could use its resources to improve constructability and productivity. One of these recommendations was to form PRO: An ACI Center of Excellence for Advancing Productivity. PRO was subsequently inaugurated in 2023, giving ACI and the concrete industry an effective and unifying new resource for positive change.

On June 27 and 28, 2023, PRO held a strategic planning workshop with broad industry participation, including designers, materials suppliers, and concrete contractors (refer to Fig. 1.3.3). The workshop's many findings included the need to improve early-phase designer-contractor interactions. This finding complements three of the seven areas identified in the MGI study:

- Rewiring the contractual framework to reshape industry dynamics;
- Rethinking design and engineering processes; and
- Improving on-site execution.

Fig. 1.3.3: PRO's first-ever Strategic Planning Workshop hosted at ACI Headquarters in Michigan.

1.4 CONSTRUCTABILITY ECONOMICS

Constructable designs lead to faster build times by minimizing the need for issuing (and waiting for responses to) RFIs, by eliminating the need for rework, and by accommodating realistic tolerances. Project financing costs are reduced; commercial projects capture revenue sooner; externalities such as traffic delays are reduced; and opportunity costs for designers, suppliers, and others are minimized (design professionals, for example, can focus on the next project rather than respond to RFIs for the last project).

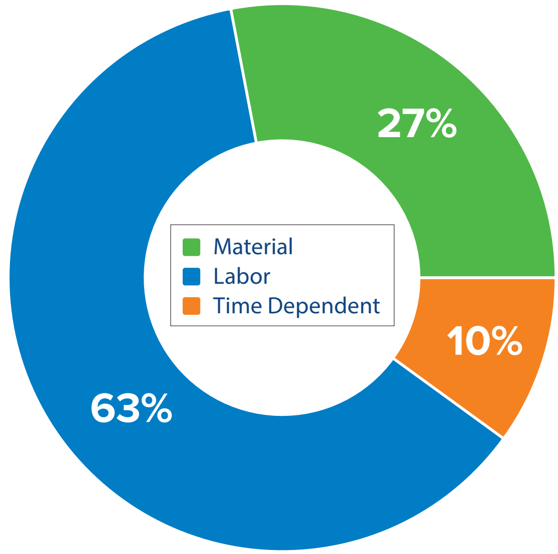


Fig. 1.4.1: The cost of labor comprises more than twice the cost of materials for a concrete construction project.

At the 2021 SDC Technology Forum, for example, a case study was presented on the constructability economics of concrete construction in the United States. The study of Ceco Concrete Construction projects determined that materials comprise 27% of the total cost of the projects, and time-dependent expenses (for example, formwork rental, hoisting, supervision, and equipment) comprise another 10% of the total cost. Labor (for example, placement of formwork, reinforcement, and concrete) comprises 63% of the total (refer to Fig. 1.4.1). Clearly, a constructable design will optimize labor and provide significant value to project owners.

Improving collaboration between the contractor and designer is critical to producing a constructable design that can improve productivity and eliminate unnecessary cost. Designers find that early concrete contractor collaboration improves design efficiency, with fewer design modifications required during construction compared to the traditional design-bid-build approach. RFIs and costly change orders during construction are greatly reduced.

1.5 COLLABORATIVE RELATIONSHIPS

A chart from **The Owner's Dilemma** (refer to Fig. 1.5.1) shows the power and potential of collaboration: While strategic purchasing and proactive problem solving in the Contractor-Designer Collaboration model provide increasing value over the project duration, adversarial change orders in the noncollaborative Design-Bid-Build model result in decreasing value over the project duration. In the former, the parties work together to enhance common project goals. In the latter, each party is focused on their own self-interest. Clearly, trusting and collaborative relationships among the contractors, designers, and project owner offer the greatest value for all parties.

A collaborative effort initiated by the Construction Users Roundtable (CURT) along with the American Institute of Architects (AIA) and the Associated General Contractors of America (AGC) has led to the introduction of contract documents supporting project teams. Integrated, value-based contractual agreements designate risks and rewards for trusting collaborative processes. These agreements should include performance-based incentives and disincentives. Collaborative teams must believe in true, fault-free collaboration. Collaboration allows stakeholders to manage risks together, effectively dismantling silos that have been previously constructed to deflect risk.

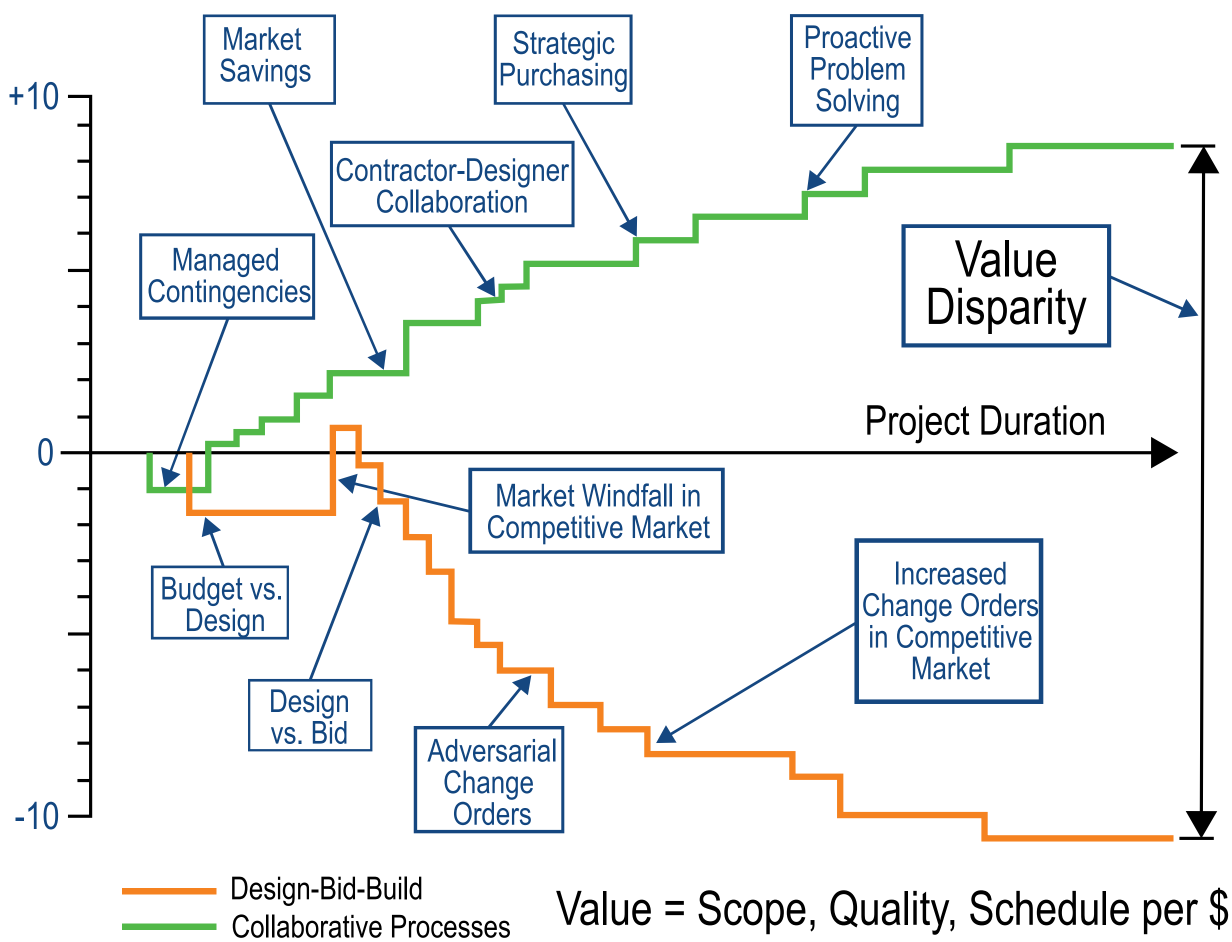


Fig. 1.5.1: Value (scope, quality, and schedule enhancements per dollar spent) can be lost within an adversarial bid environment—even in a competitive market, where significant windfalls at 'bid-time' are sometimes captured. (Bryson, B.W., and Yetmen, C., The Owner's Dilemma: Driving Success and Innovation in the Design and Construction Industry, *Ypsilon & Co., July 1, 2010, 245 pp.)*

Author Clive Thomas Cain[2] has stated that trust-based collaboration can deliver up to 30% savings in construction costs.

Integrated project delivery (IPD) with lean construction and design is a construction project delivery method and philosophy by which key parties involved in the design, fabrication, and construction aspects of a project are joined together under a single agreement. IPD can be achieved through various relationship arrangements (refer to Fig. 1.5.2), with associated degrees of collaboration and benefits. While a contractual agreement has benefits for an IPD (refer to Levels Two and Three), it is not required (refer to Level One). The key element for effective relationship arrangements is trust.

[2]Cain, C. T., "Profitable Partnering for Lean Construction," Oxford: Blackwell, 2004, 241 pp.

Mat pour. (Image courtesy of The Conco Companies.)

Degrees of Collaboration from the AGC webinar by IPD

	"Classic" Collaboration	"Non-Multi-Party"	IPD
Level of Collaboration:	Lower ⟷		Higher
Delivery Approaches:	CM At-Risk or Design-Build	CM At-Risk or Design-Build	IPD
Typical Selection Process:	Qualifications-Based Selection of all team members or Best Value Proposal	Qualifications-Based Selection of all team members	Qualifications-Based Selection of all team members
Nature of Agreement:	Transactional	?	Relational
Key Characteristics:	• No contract language requiring collaboration • Limited team risk sharing • CM or DB share in savings • Open book trust between parties • Early project commitment to designer-contractor by owner	• Contract language requiring collaboration • Some team risk sharing • All parties' compensation tied to project success • Co-location of team	• Owner-Designer-Contractor (and possibly other key team members) all sign one contract that contracts collaboration • Team risk sharing • Team decision-making • Optimizing the project • Pain/gain sharing • Limits on litigation • Co-location of team
Typical Basis of Reimbursement:	GMP	GMP	No GMP or GMP (some costs guaranteed)

Fig. 1.5.2: Levels of collaboration for Integrated Project Delivery

1.6 DESIGN COLLABORATION IS THE KEY

The design-bid-build (DBB) method creates silos (refer to Fig. 1.6.1). While DBB can ostensibly provide owners with low costs at bid time, it rarely brings the owner the lowest possible final cost. In *The Commercial Real Estate Revolution*,[3] Scott Simpson of KlingStubbins explains the illusionary allure of DBB: "The idea that a project will cost less if you don't bid is counterintuitive. Owners use bidding as a cost management tool, but inevitably end up higher than managing the cost on the front end.

Improved constructability must start with foundational change to relationships between all parties. These changes must garner new practices of trust, collaboration, and sustainability to yield the best results. Designers and subcontractors should base their team selections on tried-and-true professional relationships.

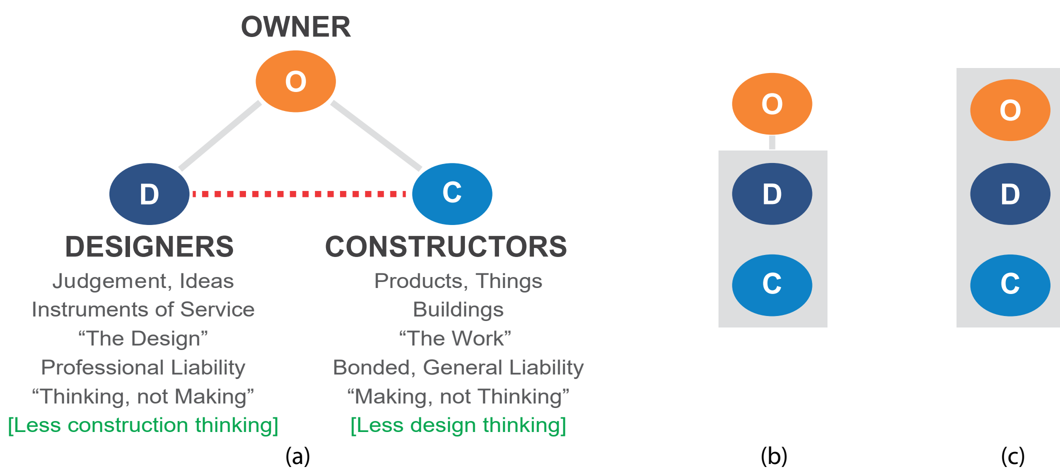


Fig. 1.6.1: The owner must work with design and constructor teams, each with its unique goals, responsibilities, purpose, and mindset: (a) Traditional Design-Bid-Build delivery creates silos and results in inefficient communication; (b) Design-Build delivery improves communication between designers and constructors; and (c) Integrated Project Delivery creates a total team mindset (Image Credit: Bernstein, P., "Integrated Project Delivery [IPD]: Why Owners Choose Multi-Party," AGC, Presentation on Oct. 29, 2009).

> *"The old design-bid-build paradigm had its day, but it has outlived its usefulness and is getting in the way of the kind of real change that can transform the way we build buildings."*
> The Commercial Real Estate Revolution

Owners who bring about the most productive projects require design consultants and contractors who are prepared to both collaborate and innovate.

Communication among trusting teams is vital to successful collaboration and increased productivity on projects. Those who are not interested in improving productivity are having increasing issues securing business opportunities, as more owners see productivity and constructability as the way to go.

---

[3]Miller, R.; Strombom, D.; Iammarino, M.; and Black, B., *The Commercial Real Estate Revolution*, John Wiley & Sons, Inc., New York, 2009, 352 pp.

1.7 TIMING OF COLLABORATION TO MAXIMIZE RESULTS

Figure 1.7.1 illustrates how collaboration from conceptual design through concrete construction saves a significant amount of time. Contractors benefit, as collaboration maximizes constructability gain. Designers benefit, as time required for redesign and design clarifications is reduced or eliminated. Lastly, owners benefit, as early project design collaboration results in better quality and reduced financing cost.

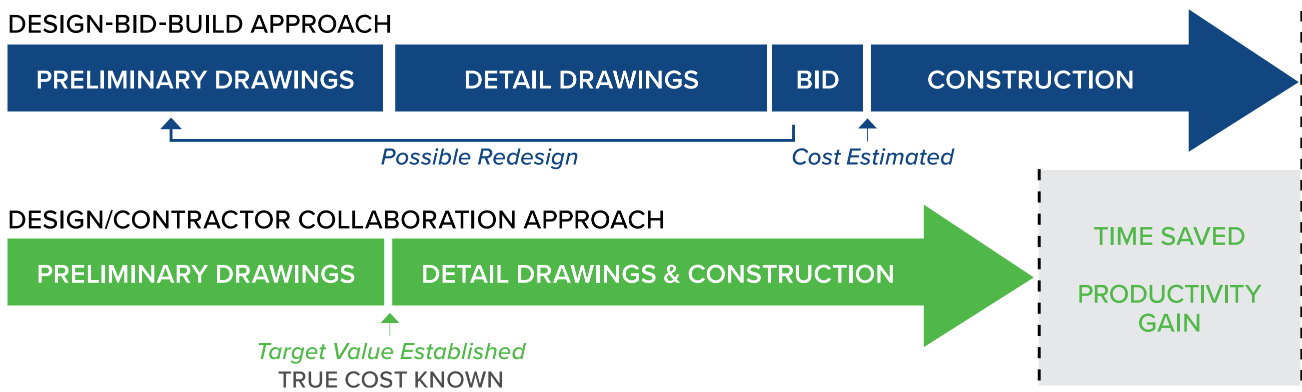


Fig. 1.7.1: IPD adds value through collaboration.

In contrast, the traditional DBB delivery system results in delayed collaboration and/or contentious interactions between designers and constructors, demanding more time and cost expenditures than are needed for projects with early design collaboration. In brief, late-stage design changes can significantly impact the construction of a project (Fig. 1.7.2).

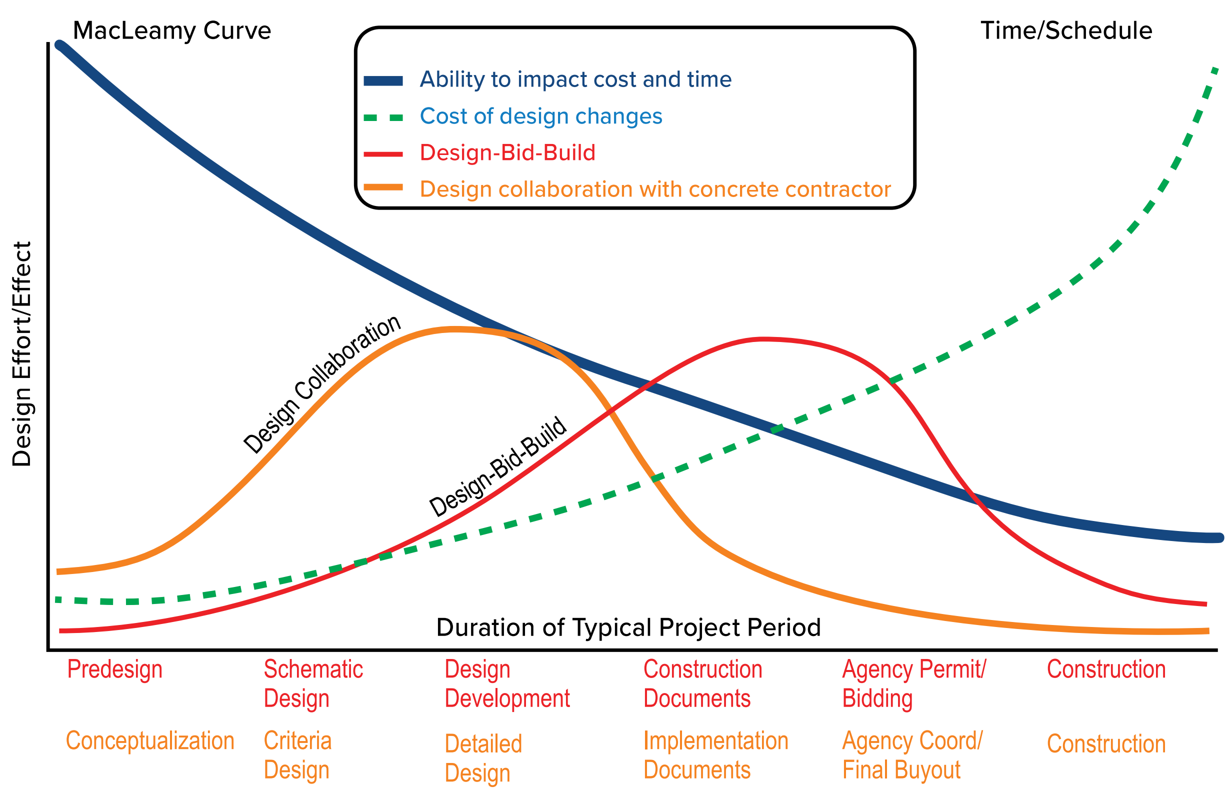


Fig. 1.7.2: The MacLeamy Curve demonstrates the benefits of early collaboration on decisions (after The Owner's Dilemma*).*

In the DBB approach, as illustrated in Fig. 1.7.3, the contractor is selected later in the preconstruction phase. Unfortunately, because many key design decisions has already been made, the benefits offered by the contractor's knowledge of constructability and productivity improvements are lost.

Fig. 1.7.3: When the major trade subcontractors are hired in a traditional DBB delivery approach, significant intelligence is added to a project. Because these subcontractors are brought in well after preconstruction design and planning is nearly complete, however, major opportunities to improve constructability are lost.

To achieve collaboration, all major members of project teams should be identified and hired during the predesign phase, including the concrete subcontractor. Major subcontractors should be included in the creative sessions to leverage cost-saving strategies early in the project. The key point is to engage the constructability team in the early planning and design phases.

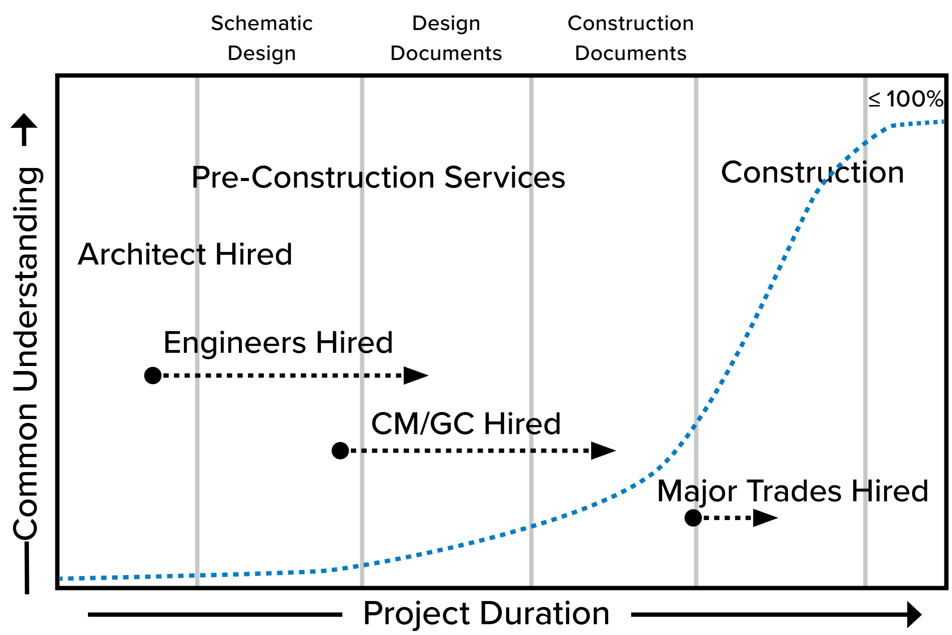


Fig. 1.7.3: Illustration of the significant intelligence that is added to a project when the major trades are hired, often after preconstruction design and planning is nearly complete. The late addition of the major trades reflects a missed opportunity to improve constructability during design.

1.8 OUTCOMES OF CONSTRUCTABILITY FOCUS

The positive effects of a constructability focus are realized by all stakeholders. The collaborative team of designers, general contractors, and key subcontractors will more fully develop design solutions with less coordination and risk of costly redesign, plus a reduced risk of innovation. Stakeholders can focus on work satisfaction in lieu of confrontational stress, leading to owner satisfaction with innovative structural concrete solutions.

PRO Recommendations:

- *Hire trusted designers, general contractors, and key subcontractors in the early design process and pay for preconstruction services; seek construction firms that have proven design-assist skills.*
- *Assuming contractors provide value, capture the preconstruction input of the contractor and key subcontractors by proceeding to construction with them.*

(Image courtesy of Ceco Concrete Construction.)

1.9 CONCRETE'S DESIGN ADVANTAGES VERSUS CONSTRUCTABILITY

Concrete gives architects and engineers creative design freedom, and its locally available materials reduce supply chain challenges and enable faster construction starts. However, concrete's design flexibility can compromise constructability if designs are not carefully evaluated.

Contemporary designs, for example, can challenge designer/contractor teams with significant obstacles to maintaining efficiency. On such projects, the traditional design-bid-build process often results in an unproductive and unconstructable design, accompanied by expensive delays and change orders. Thus, the design freedom offered by concrete construction also increases the value of designer/contractor collaboration.

Multi-story high-rise undulated slab edge completed through constructable design practice. (Image courtesy of Ceco Concrete Construction.)

1.10 THE PATH TO CONCRETE PRODUCTIVITY—A SUMMARY

Improving concrete construction productivity requires change. PRO suggests the following as a first step for owners, designers, contractors, and other project stakeholders interested in better constructability, which will lead to improved construction productivity:

- Overcome the false sense of security obtained with the traditional design-bid-build (DBB) delivery method. The traditional method precludes early design collaboration, which is the greatest opportunity for developing significant project value and project cost savings.
- Identify and select designers, contractors, and subcontractors who have proven collaboration skills, business ethics, and industry relationships.
- Establish the designer/contractor/material supplier team at the conceptual design stage.
- Establish a contract framework to define expectations.
- Take proactive steps to maximize stakeholder communication and trust while minimizing stakeholder risk.
- Reward innovative concepts, investigations, and analysis of "game-changing" solutions.
- Pay premium design fees and contractor markups that reflect the knowledge, skills, and creativity the team contributes to project success.
- Avoid design changes late in the process, as they will have a "domino effect" that can have major impacts on productivity and disrupt an optimized construction plan.
- Finish the project as a collaborative team, in the same spirit of cooperation as at the start of the project.

1.11 ADDITIONAL RESOURCES FOR THOSE SEEKING TO IMPROVE CONCRETE PRODUCTIVITY

PRO: An ACI Center of Excellence for Advancing Productivity will continually update and expand the Constructability Blueprint by incorporating design and construction concepts, case studies, and much more. PRO is also developing additional resources, and other organizations offer complementary programs and documents. For more information, visit www.concreteproductivity.org. Additional information is available through the following resources:

- ACI University offers many webinars, on-demand courses, and certificate programs relevant to designers and constructors, including its Constructability Certificate Program covering planning, layout, project delivery, project site drivers, structural system concept design, and more. Visit www.concrete.org/education/aciuniversity.aspx.
- The Lean Construction Institute (LCI) provides many resources on Integrated Project Delivery. Visit www.leanconstruction.org.
- The Design-Build Institute of America is dedicated to helping members achieve collaboration-driven success, and it helps connect owners and industry looking for qualified team members. Visit www.dbia.org.
- The American Society of Concrete Contractors is committed to helping concrete contractors improve their businesses and their roles as contractors by providing the tools to grow business and provide the highest quality product. Visit www.ascconline.org.

An ACI Center of Excellence for Advancing Productivity

Constructability BLUEPRINT

SECTION 2: CONSTRUCTABLE DESIGN PRINCIPLES

2.1 PATHWAYS TOWARD CONSTRUCTABLE DESIGN

Early project stakeholder involvement maximizes constructability outcomes with value-based design decisions. Stakeholders should include project ownership, designers, and concrete contractors from the conceptual stage. Design input from a trusted builder often allows the designer to consider unique and innovative alternatives regarding materials, sequencing and scheduling, construction logistic considerations, prefabrication, component assemblies, and field labor safety and efficiency (Fig. 2.1.1). While this design collaboration will often improve designer effectiveness and timeliness, early partnering with builders is not always possible. To help all design teams recognize opportunities for efficiencies, even without early collaboration, this section of PRO's Constructability Blueprint provides constructability concepts and principles.

Fig. 2.1.1: Through early collaboration with experienced concrete contractors, designers can optimize designs to take full advantage of the unique features of concrete construction. (Image courtesy of Ceco Concrete Construction.)

2.2 CODE-COMPLIANT DESIGN VERSUS CODE-CONSTRUCTABLE DESIGN

While some may believe that designing concrete structures for constructability achieves cost reductions and shortens schedules by cutting corners, this simply is not true, as all concrete buildings constructed in the United States must be designed in accordance with the minimum requirements of ACI 318—no exceptions. However, not all code-compliant designs are readily constructed, as concrete members may meet code, yet have zones with congested reinforcement, cumbersome formwork requirements, or conflicts with mechanical, electrical, or plumbing systems.

Structural engineers generally strive to optimize the cost of structures, often by using modern design software tools to minimize the sizes of structural members. Placing excessive emphasis on minimizing the size of concrete members, however, can lead to unintended consequences that may defeat the constructability goal of minimizing the construction cost for the overall project (Fig. 2.2.1). 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 (refer to **Designing to Minimum Concrete Dimensions**). Conflicts can also be created by the inadequate coordination of reinforcement for the member in question, reinforcing bars from intersecting members, and embedded anchor bolts or headed studs. Such conflicts can potentially lead to honeycombs and voids in the concrete, inadequate cover, and inadequate embedment. Optimizing the design of individual members can also result in similar, but not identical, members. This can significantly impact costs by limiting reuse of the formwork, as well as increasing the quantity of unique reinforcing assemblies and thereby reducing worker productivity.

Fig. 2.2.1: Designers must be aware of the need to place and consolidated concrete. (Image courtesy of Ceco Concrete Construction.)

The ACI 318 Design Code establishes limits for maximum reinforcement (for example, ACI 318 Sections 9.3.3.1 and 10.6.1.1), minimum flexural reinforcement (for example, ACI 318 Section 9.6), and minimum reinforcement spacing (for example, ACI 318 Section 24.3.2). These limits are imposed to mitigate brittle flexural behavior in case of an overload, to ensure beams can sustain loading after the onset of flexural cracking, and to control cracking under normal service conditions, respectively. While they are not imposed to ensure constructability, the underlying expectation in all provisions is that design engineers will use their judgment when design parameters approach code limits. Consultation with an experienced contractor can greatly help in these decisions.

Simply stated, a code-compliant design is the minimum requirement, but a code-constructable design provides value to the owner with cost and schedule benefits. Further details will be available in “ASCC Guide to Design for Cast-in-Place Concrete Constructability,” to be published in the December 2024 issue of *Concrete International*.

2.3 PERMANENT MATERIAL VERSUS CONSTRUCTION LABOR AND TIME

During the engineering process for concrete frames, the common approach in theory and practice is to search for ways to reduce the quantity of materials in the completed structure. While those efforts have merit in reducing structural weight, embodied carbon, and material costs, to concentrate solely on reductions in permanent material is to overlook the most important influence on concrete structural frame costs: construction labor.

Increases in these transitory costs can inflate the total cost of a concrete frame, even as the total quantities of permanent material are reduced. A recent case study of a highly constructable reinforced concrete building in a high-labor-cost market (refer to A Case Study on Constructability Economics) demonstrated that the cost of the permanent materials (concrete and reinforcement) in the building's frame comprised only 27% of the total cost of construction, while the cost of the labor required for erecting formwork; placing reinforcement; pumping, placing, and finishing concrete; and logistics, hoisting materials, and ensuring safety comprised 63% of the total (Fig. 2.3.1). In this and other examples, labor weighs heavily on the total cost, so it's clear that focusing early design efforts on optimizing labor utilization can be critical for maximizing owner value (Fig. 2.3.2). While every project may differ, the described case study illustrates the potential design impact on the owner's value when a design is focused on labor and time (60 to 70% of total cost), in addition to material quantities. These values will be reduced in a low-labor-cost market. Although forming is not a tangible feature of the finished structure, it represents 22% of the total structure cost in this highly constructable building. In structures designed without an emphasis on optimizing formwork, however, this cost can reach 50% of the total cost.

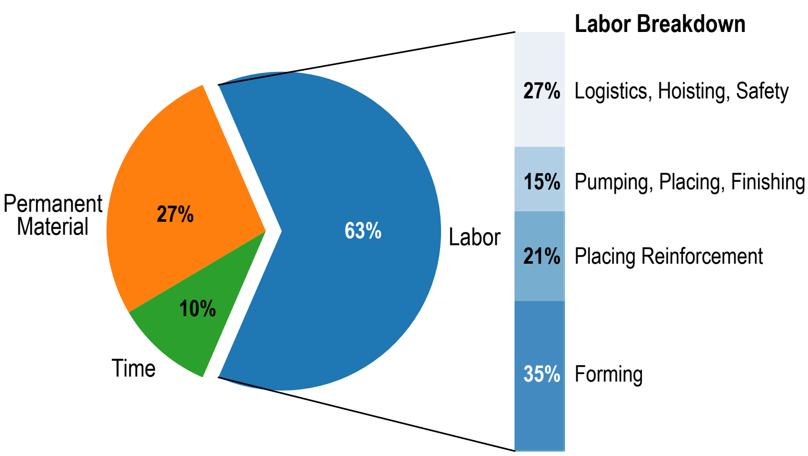


Fig. 2.3.1: A recent analysis of a reinforced concrete building structure showed that labor comprised most of the cost of construction, while permanent material and time (time-dependent costs such as equipment rental) comprised only 27% and 10% of the total cost of construction, respectively. Note: percentages may not total 100 due to miscellaneous costs and rounding (after "A Case Study: Constructability Economics – Why Constructability Is Important").

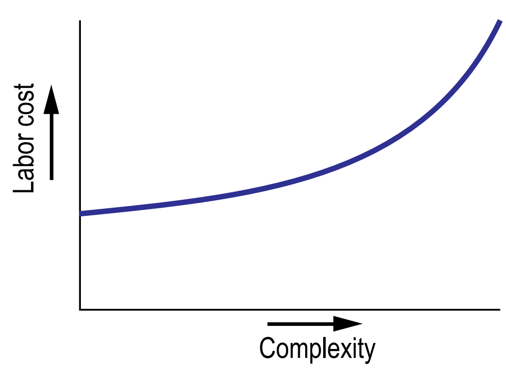


Fig. 2.3.2: Labor costs can increase exponentially with increasing complexity.

2.4 WHERE TO START AS A DESIGNER

At the conceptual structural design stage and before design refinement, the designer should envision common, repetitive-sized structural members with a conservative bias toward oversized structural elements if necessary due to time constraints. Later in the design process, reducing element sizes to accommodate architectural, mechanical, electrical, or plumbing requirements will be easier than increasing sizes to improve constructability. However, the decision to reduce an element size should not be made singularly, as isolated modifications will lose the constructability advantages of element size repetition. As the design process progresses, the designer can focus on achieving material efficiency in conjunction with ensuring constructability of the structural elements. Structural material quantities for concrete and reinforcement will vary within predictable ranges. Fundamentally, material quantities are affected by multiple external factors and system choices (Fig. 2.4.1) as well as the function of specific structural elements (Fig. 2.4.2).

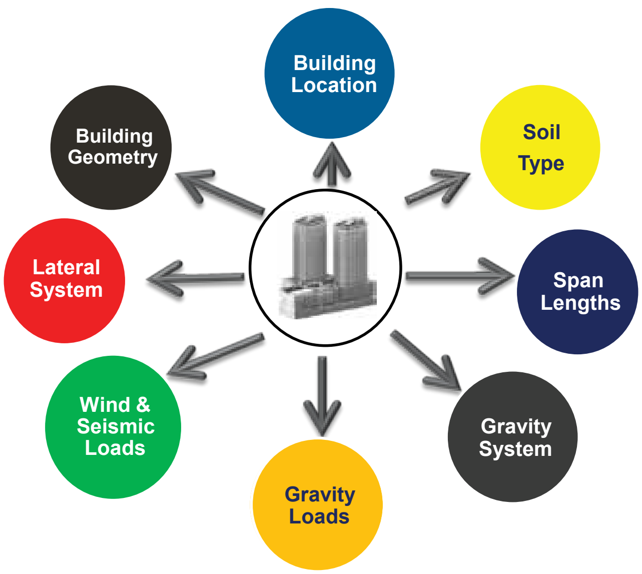


Fig. 2.4.1: Factors affecting material quantities in a concrete building structure. (Image courtesy of CKC.)

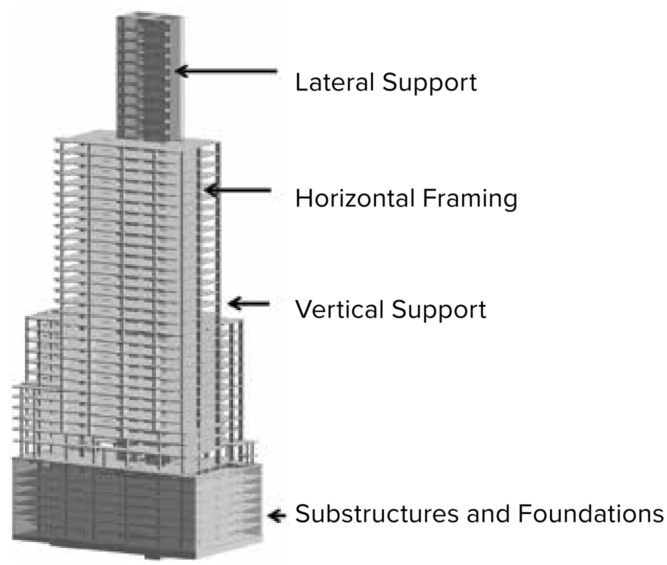


Fig. 2.4.2: Schematic illustration of primary structural components in a mid- or high-rise structure. (Image courtesy of CKC.)

The total quantity of reinforcing steel required in a building will typically range from 7 to 14 lb/ft^2 (34 to 68 kg/m^2) of elevated deck. And as shown in Table 2.4.1, this total can be largely impacted by the design decisions affecting the lateral system and the horizontal framing.

***Table 2.4.1: Common ranges of reinforcement required in primary structural components.** (Table courtesy of CKC.)*

System	Reinforcement type	Weight per unit of floor area, lb/ft^2 (kg/m^2)
Lateral support (walls and/or frames)	Mild steel bars	1.0 to 4.5 (4.9 to 22.0)
Vertical support (columns)	Mild steel bars	1.0 to 2.0 (4.9 to 9.8)
Horizontal framing (slabs and beams)	Mild steel bars	1.5 to 3.0 (7.3 to 14.6)
	PT tendons	0.7 to 1.2 (3.4 to 5.9)
Substructure and foundations	Mild steel bars	0.5 to 2.5 (2.4 to 12.2)
Miscellaneous	Mild steel bars	1.0 to 3.0 (4.9 to 14.6)

Throughout the design phases, the designer must consider concrete construction tolerances as established in **ACI 117-10**, “Specification for Tolerances for Concrete Construction and Materials,” as establishing and coordinating tolerances are the responsibility of the licensed design professional (refer to **Concrete Q&A on Coordinating Tolerances**). Be aware that many finish trade tolerances—for example, those for window wall systems—are tighter than associated concrete construction tolerances. This tolerance delta can become a scope gap leading to conflict and displeased project owners.

Concrete construction tolerances include those on reinforcing steel, so designers should proactively develop design details to address and mitigate tolerance conflicts that can surface in congested reinforcement locations. Mitigating a reinforcing tolerance conflict during construction is difficult, expensive, and time-consuming. Usually, the best solution is to modify the formwork to accommodate the reinforcement.

Improving constructability during design can be daunting. Start by considering local weather and environmental demands. If possible, evaluate the availability of local construction skills, practices, and culture. Then focus on the key structural elements, making them efficient and constructable. Figure 2.4.3 illustrates the relative costs of three structural elements: horizontal framing, column and bearing walls or vertical support, and lateral restraint system. Horizontal framing is often the most expensive and should be optimized for constructability. As a structure increases in height, optimizing the lateral restraint system becomes more important.

Floor framing will become more economical as the number of uses increases, provided the design has repetitive element sizing, allowing increased use of the formwork. Repetitive designs also take advantage of a construction crew’s learning curve (Fig. 2.4.4). Every nonrepetitive change is a setback to the crew’s productivity gain from repetition. This illustrates a key form-work metric of achieving a constructable design. Advanced formwork systems have sizable mobilization, make-up, form tear-down, and learning curve costs that are effectively recovered as use increases. Thus, a design that requires single-use formwork is less constructable and more expensive. The structural cost varies greatly without a significant change in the material quantities, primarily due to achieving constructability during design.

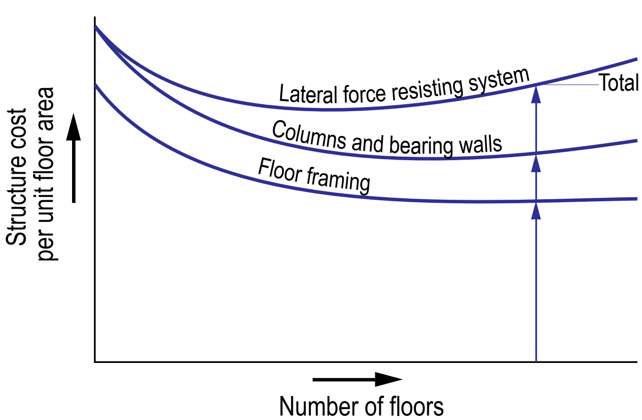


Fig. 2.4.3: Schematic illustration of relative costs of three structural elements as a function of building height. Labor costs will decrease to an optimum value as workers gain experience and mobilization costs become less of a factor. Thereafter, the unit cost of floor framing will remain constant with increasing height. However, increasing loads will cause the unit costs of columns, bearing walls, and the lateral force-resisting system to increase with increasing structure height.

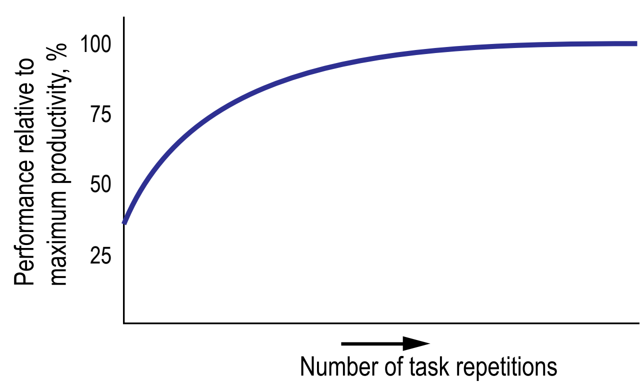


Fig. 2.4.4: Schematic learning curve for a formwork crew. The crew’s productivity plateaus after a rapid increase as they become familiar with the formwork and structural systems.

2.5 HORIZONTAL FRAMING

The largest contributor to the total cost of a structural concrete building is the horizontal (floor) framing, so optimizing floor framing for constructability should be a high priority in design. There are many basic floor framing design approaches (Fig. 2.5.1). Each has differing span and load capabilities, as well as unique qualities and advantages (Table 2.5.1). For example, pan slab construction will offer the designer capabilities of longer spans, higher design loads, stiffer slabs, and reduced materials. The designer should consider the constructability advantages and disadvantages of the floor system during the conceptual design stage, using the quick tips as well as other formwork, reinforcement, and pump/place/finish constructability logic contained in the following chapters as the design process advances.

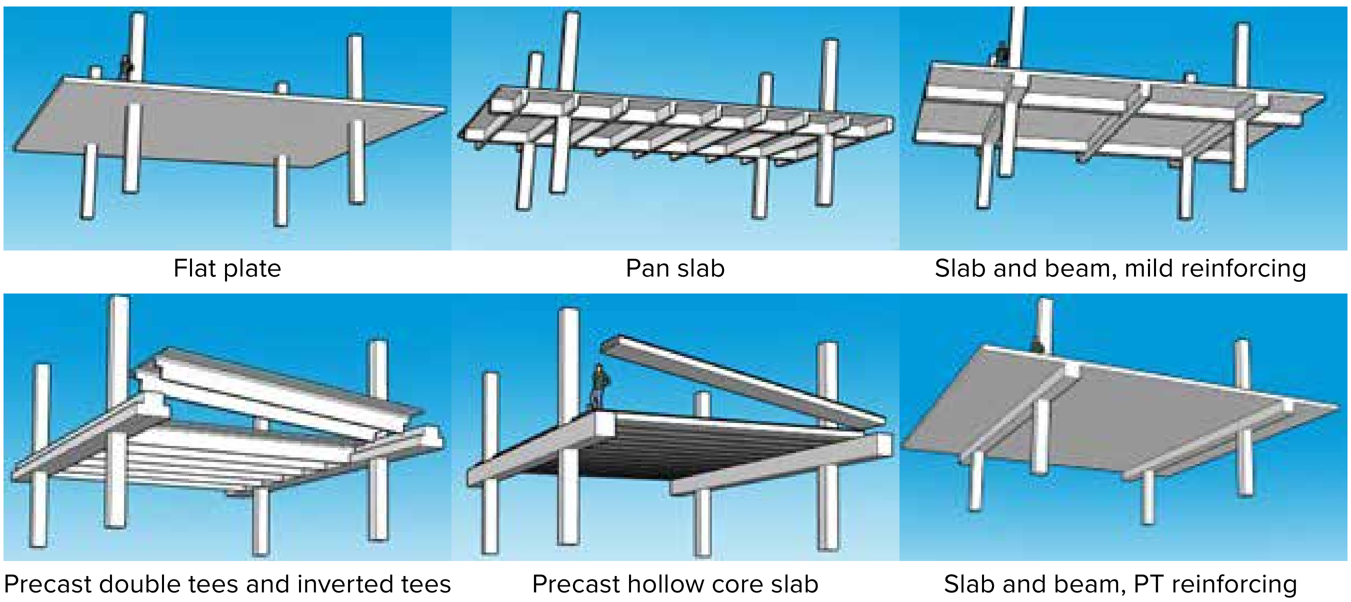


Fig. 2.5.1: Illustrations of various floor framing systems.

Table 2.5.1: Key characteristics of basic floor framing systems, including typical spans

Basic floor framing system	Typical spans, ft (m)	Constructability advantages	Constructability disadvantages	Quick tips
Flat plate, mild reinforcing	Up to 25* (7.6)	Productive	Many columns, camber	Align columns
Flat slab (drop panels), mild reinforcing	Up to 30* (9.1)	NA	Low productivity	Repetitive drop panels, no camber
Flat plate, PT reinforcing	22 to 32 (6.7 to 9.8)	Productive, no camber	Pour strips	Use double-headed stud anchors (stud rails) to resist shear
Precast hollow core	30 to 40 (9.1 to 12.2)	Rapid assembly	Bearing walls or beams	Lead time needed for offsite fabrication
Pan slab, mild reinforcement	25 to 45 (7.6 to 13.7)	Standard, reusable forms	Best for multiple uses	Integrate beams at soffit depth
Pan slab, PT reinforcement	30 to 55 (9.1 to 16.7)	Standard, reusable forms	Best for multiple uses	Use wide modules
Precast double tees and beams	40 to 60 (12.2 to 18.3)	Rapid assembly	Crane and logistics, support beams	Standardize spans, lead time for fabrication
Slab and beams, mild reinforcement	20 to 40 (6.1 to 12.2)	Non-repetitive areas	Low productivity	Standardize beam depths
Slab and beams, PT reinforcement	40 to 60 (6.1 to 18.3)	Productive use of standard forms	Pour sequencing and pour strips	Standardize bays, beams, columns

*Spans based on 10 in. (250 mm) slab. Note: NA means not applicable.

2.6 FORMWORK LOGIC

As noted in Chapter 2.3, forming labor is a large cost component. Although formwork costs can be as much as 50% of the cost of a concrete structural frame, formwork is often the most misunderstood component for designers because it is invisible during the design process and rarely is left permanently behind upon completion. Fortunately, it is also the component that yields most readily to a constructability strategy in both labor productivity and time. Standardizing structural elements will also reduce the opportunity for error. If a designer can take a pragmatic formwork logic approach and visualize the forms and field labor required to form various structural members, improving constructability is possible (refer to *Concrete International* article, Formwork Efficiencies, June 2008).

Consider the following formwork logic:

(a) **Building element geometry:** Consistency in structural element geometry can maximize the reuse of formwork materials, which leads to increased constructability. Planning element geometry consistency within an area and from floor-to-floor will improve constructability, as varying geometry leads to the need for custom formwork specific for each use or location. Custom formwork is not a desired or timely solution, even if structural materials are highly efficient. Consistent patterns are preferred over irregular ones. Creating gang forms from panels can increase productivity, whereas dimensional changes require customization that reduces productivity (Fig. 2.6.1). As shown in the figure, a uniform, symmetrical (Plan A) column pattern facilitates the use of high-productivity systems such as gang or flying forms for the horizontal structural system. Scattered and irregular positioning (Plan B) may eliminate the possibility of using these productive systems, and it will require the fabrication of custom geometries of sheathing material.

(b) **Sizing concrete members:** Size concrete members based on formwork economy. When possible, lay out column locations in a repetitive manner. Minimize the number of column size changes. Keep the same beam width and depth throughout the structure (Fig. 2.6.2) and vary the amount of reinforcement as indicated by structural demands.

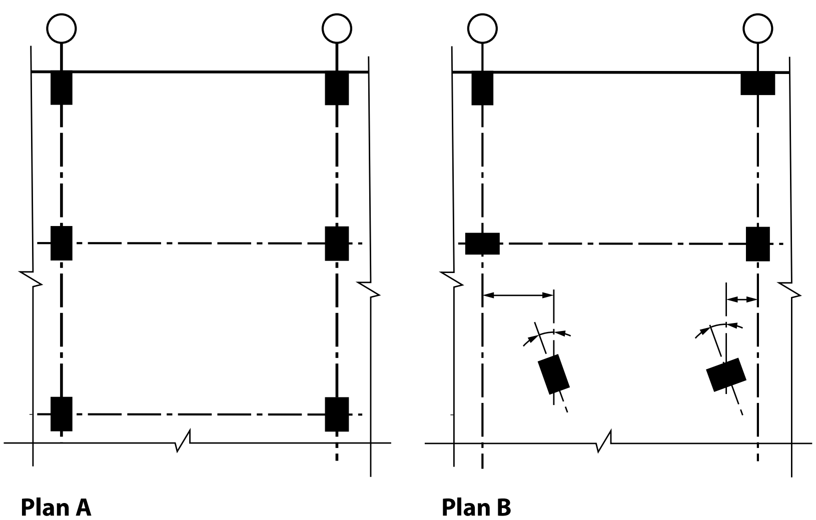


Fig. 2.6.1: Consistency and repeatability are critical for constructability. In contrast to Plan B, the columns in Plan A have consistent size and orientation, allowing the contactor to design and furnish advanced table panel floor formwork and reduce likelihood of layout errors.

Fig. 2.6.2: When possible, use the same column size and geometry over the full area of the building and maintain column sizes over at least 10 floors. (Image courtesy of Ceco Concrete Construction.)

(c) **Use of formwork material:** Formwork material use is a key planning element for every concrete contractor. The contractor must consider several variables in the planning process, seeking optimum results on every project. These variables include the cost, time, and logistical space for formwork mobilization and de-mobilization, as well as the labor cost and time to make-up handset forms, gang forms, table panels, or more complex self-climbing formwork systems to meet the dimensional requirements of the structural elements in a project.

In this context, "make-up" is the process of assembling materials and components necessary to form designed structural elements. Most formwork comprises standardized components assembled to achieve the size and spacing of the designed structural elements by supporting the concrete and reinforcing loads during concrete pours (Fig. 2.6.3). Forms may be fabricated specifically for a single project. The high initial investment associated with customization can be justified if the project scope allows sufficient multiple uses. However, adequate lead time prior to site delivery and assembly of the customized formwork is essential.

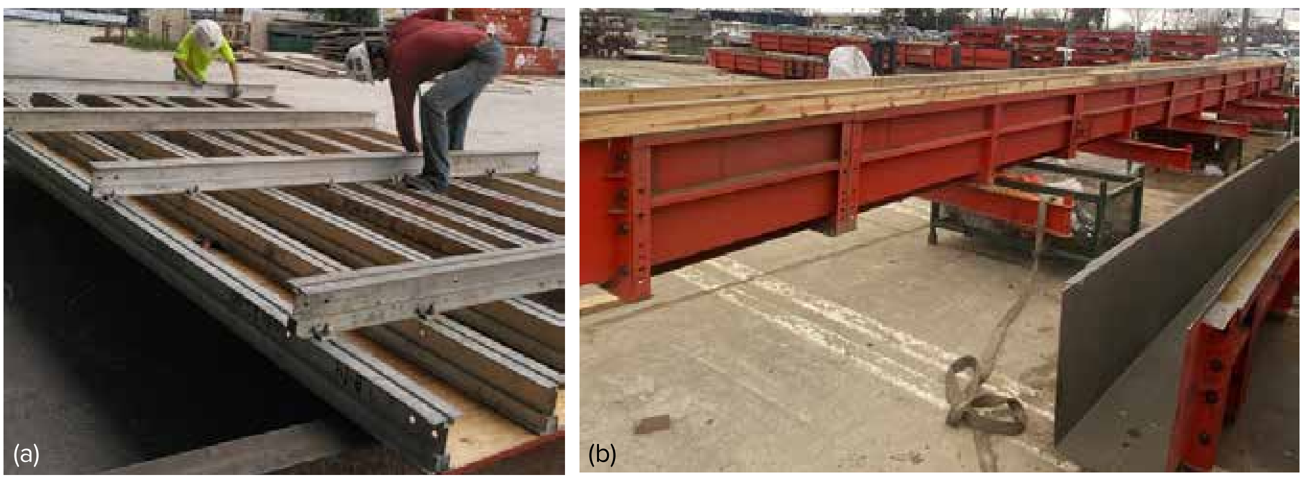


Fig. 2.6.3: Workers engage in the make-up of formwork: (a) a gang panel using standardized components; and (b) a 60 ft long steel beam form with drafted sides. (Images courtesy of Ceco Concrete Construction.)

The time required to assemble and disassemble a system is a key factor, as is the potential for productivity gains while in use. In other words, as the sophistication of formwork systems increase, the concrete contractor must consider not only the fixed cost of each system but also the learning curve required to achieve the potential of the system. Of course, the higher the number of formwork reuses without modification, the greater likelihood of a productivity gain that can result from the investment.

Figure 2.6.4 illustrates this concept for three formwork systems. The total cost function for each system is represented as form material purchase or rental cost, make-up and tear-down labor, plus labor for each use. The single-use system has a low initial cost, but it will require make-up for each use and the labor cost also will be high; the high slope reflects both factors. The gang form system has a higher initial cost than the single-use formwork, but it will require less make-up and labor for each use. At some number of uses A, the total cost of using the gang form will match the total cost of using the single-use form. Up to that point, the single-use formwork system is the proper solution. The complex system has a high initial total cost comprising make-up, form cost, and tear-down labor (high fixed cost or investment), but the labor costs for each use are low (as reflected in the lower slope due to increased productivity the system provides after the learning curve has plateaued). Panelized systems such as gang forms (Fig. 2.6.5) have an intermediate initial cost (make-up, form cost, and tear-down labor), and the labor cost (slope) is slightly higher (less productive) than for the complex system. At some number of uses B, the total cost of using a complex formwork system will match the total cost of using a single-use formwork solution. Similarly, with sufficient uses, a complex formwork system may be justified over a gang form. Of course, the number of reuses is not the only factor that must be considered before a final formwork system selection can be made.

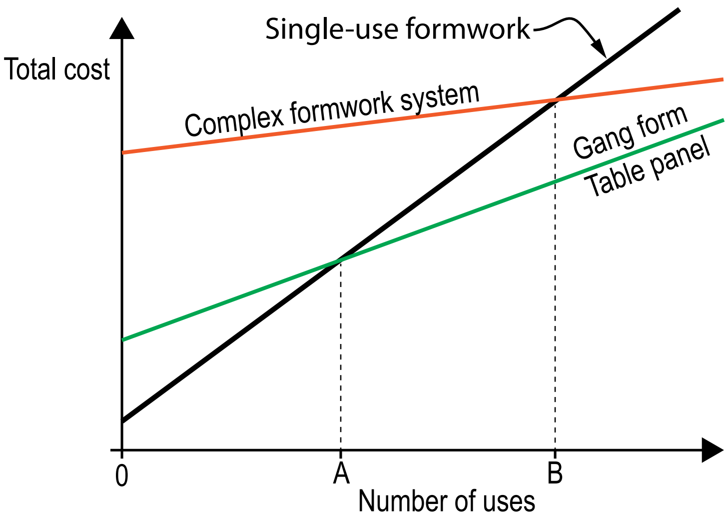


Fig. 2.6.4: A schematic representation of a contractor's evaluation of the financial impacts of highly productive formwork applications on a project. Complex formwork systems include multi-use, high-production systems and/or self-climbing systems.

Fig. 2.6.5: Workers engage in the make-up of a large gang form. Larger panels require onsite labor, area, time and hoisting to support the make-up. Further, they are too large to assemble off site and truck to/from the site. A similar disassembly process is required upon completion of use. (Image courtesy of Ceco Concrete Construction.)

If a designer asks multiple concrete contractors to offer formwork material optimization recommendations on a particular project, each contractor may offer a unique solution. Although the designer might conclude that none of the recommendations are correct, it's more likely that all are correct. This dichotomy can exist because each contractor's recommendations will be based on multiple and diverse factors, including:

- Historical experience with the formwork systems required to construct the project;
- The skill sets required to efficiently apply the systems;
- Availability of personnel with the required skill sets;
- Availability of the required formwork materials (owned or rented);
- Relationships with formwork vendors and/or subcontractors; and
- The existence of local ordinances precluding the use of some systems.

Even if design collaboration potential cannot be captured, the designer can enhance constructability by making structural elements as repetitive as possible, thereby allowing the concrete contractor to consider avenues for maximizing formwork material use and advanced formwork systems. Designers should also be aware that every dimensional change in structural elements requires the contractor to conduct a new "use analysis" of formwork materials. The analysis may conclude that existing formwork material can be modified efficiently and in a timely manner. If the analysis determines that additional formwork material is required, however, the contractor must create a new assessment of the make-up needs, the mobilization and demobilization processes, and the associated labor cost and time requirements.

(d) **Minimize formwork material required:** It is to the project owner's benefit that the concrete contractor minimizes formwork material on site while maximizing productivity (labor efficiency and time). Concrete contractors plan to optimize the amount of formwork material on site. Maintaining a consistent structural system (Fig. 2.5.1) throughout a project enables the contractor to minimize formwork material required and improves constructability. Having too little material will delay project completion, and a lack of crew continuity will harm productivity. Having too much formwork material on site adds to the costs of mobilization, make-up, and demobilization. In addition, too much formwork material can consume highly valued staging space needed for other logistical needs. This can also delay projects, as finishing trades can be blocked from initiating needed tasks. On larger project footprints, having deck formwork sufficient for three placements is ideal: While one deck is being placed, the second has reinforcement installed, and the third is in the curing and formwork removal process (Fig. 2.6.6).

Many concrete contractors will vary placement sizes from 7000 to 15,000 ft^2 to enable the three-deck formwork material placement cycle. On projects with smaller footprints, the concrete contractor will typically plan on having one or two deck placements per floor, seeking to minimize the formwork material for those placements and reusing the formwork vertically. Concrete contractors ideally plan the formwork for columns and walls to be in sync with the deck formwork placements. This means they will supply one deck placement of the vertical structural element formwork, plus any special sizes, then reuse the forms for each deck. As a designer, capture formwork productivity by using similar vertical structural elements in subsequent placements (Fig. 2.6.2). If not, then additional vertical formwork material will be required and specialized formwork will be underutilized until the single need arises.

Fig. 2.6.6: Ideally, sufficient formwork should be available to place concrete in one section, place reinforcing in a second section, and complete curing and formwork removal in a third section. A three-pour concept, as shown in these examples, is desired by contractors to provide labor force and labor task continuity. Both benefits will increase productivity of the crew and individual craft personnel, maximizing their progression on the learning curve (refer to Fig. 2.4.4). (Images courtesy of Conco (top) and Ceco Concrete Construction (bottom).)

(e) **Minimize variations in beam and column sizes:** Minimizing changes in beam and column sizes lowers formwork costs and speeds construction because it avoids the need to supply additional formwork materials and make-up additional forms (Fig. 2.6.7). By minimizing changes in member size, designers improve the efficiency of formwork material use and reduce the risk of logistics errors associated with storing and retrieving multiple sizes of beam and column formwork stored on site. This boosts productivity for installation and quality control operations, and it helps to avoid the need for rework. Because of these efficiencies, experienced contractors recommend that designers maintain consistent beam sizes throughout a structure and limit changes in column size to no more than once every 10 floors. Data tip: Assembled column forms can be used more than 50 uses.

Fig. 2.6.7: Workers engaged in the assembly (make-up) of a column form. (Image courtesy of Ceco Concrete Construction.)

(f) **Formwork panels and mechanized movement:** If sufficient formwork uses justify the cost of mobilization, make-up, and demobilization of formwork panels, concrete contractors will seek to maximize the size of such panels. A simple rule of thumb is: 10 formwork reuses or more justifies gang or panel formwork. Twenty or more uses are necessary for more sophisticated formwork systems such as core wall formwork that may include self-climbing hydraulic systems. However, because the weights of gang or panel formwork systems exceed human capacity, mechanized movement, such as crane service, is necessary (Fig. 2.6.5 and 2.6.8). Cranes have both capacity and reach limits, with capacity declining as reach increases. Large capacity and reach requirements increase crane cost and the site area required to operate. Large gangs and panels require site area for make-up and tear down. Often when hoisting the panels, movement is limited by air rights of neighboring properties, or pedestrians and traffic below. Crane operation requires proper visibility and can be subject to wind and weather conditions. If contractor/designer collaboration is possible, then so are the possibilities to optimize formwork panel size and crane selection/location. Remember that the cost and limitations of hoisting highly productive formwork systems can become the contractor's limiting factor to the designer's effort to maximize concrete construction productivity.

Fig. 2.6.8: Movement of panelized formwork systems requires crane time, capacity, reach and clear area below the load when beyond the building perimeter: (a) lifting a perimeter table panel to the next level; and (b) hoisting an interior core wall gang form. (Images courtesy of Ceco Concrete Construction.)

(g) **Enhance formwork removal efficiency:** Making a few simple design adjustments can greatly improve formwork removal and reuse. Concrete contractors generally consider wall pilasters (Fig. 2.6.9) to be counter to productivity, and so recommend encasing columns within the wall (refer to Fig. 2.6.10 Plan A for best constructability). However, if pilasters are necessary, they should extend on only one face of the wall, and they should be detailed to allow 1:12 draft on each of the "parallel" faces (as shown in Plan B.) Designing a standard spacing L and standard width x can further improve pilaster productivity by allowing multiple uses of an assembled gang wall form.

Fig. 2.6.9: Example of gang wall formwork with non-drafted pilasters. (Image courtesy of Hensel Phelps.)

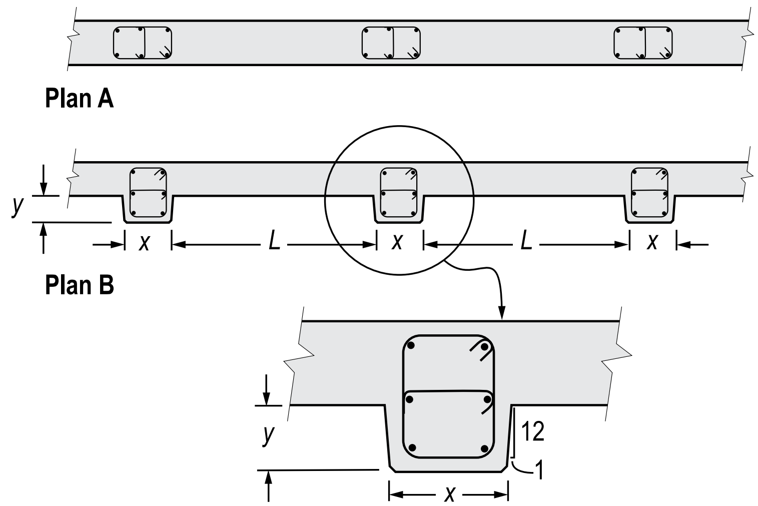


Fig. 2.6.10: Pilasters increase the complexity of wall formwork, thus diminishing construction productivity. In the preferred alternative (Plan A), pilaster reinforcement is contained within a wall and the wall formwork has a planar surface. If pilasters must extend beyond one face of a wall (Plan B), the construction documents should provide a simple detail or note allowing the contractor to provide draft. (Image courtesy of Ceco Concrete Construction.) Another constructable pilaster design alternative is increasing the pilaster reinforcing tie size and spacing to allow shotcrete to be used. Refer to Fig. 2.12.10. (Image courtesy of Conco.)

Providing a draft on the pilaster extensions allows panelized pilaster formwork to be removed without complete disassembly, and it can be reused without form repair. The same principle can be applied to interior beam sides for repetitive beam sizes that warrant a ganged beam formwork. Specifically in parking structures, repetitive beam formwork is often made from steel, allowing 60 ft long forms to be moved, installed, and removed in a single unit (Fig. 2.6.3(b)). However, for this formwork system to be considered, the beam sides must have at least a 1:12 draft to allow the form to release from the concrete after curing. While a small amount of additional concrete may be required, the productivity value realized by the project owner can be significant. Allowing beam sides to have 1:12 draft can offer similar benefits in other structures with repetitive beam sizes, thus allowing the contractor to consider the use of gang beam forms. Providing designs with consistent beam sizes allows forms to be used multiple times, with disassembly required only after the completion of the last placement.

The designer should also take every measure to avoid details that call for reinforcement or embeds to extend beyond the surface of the concrete (Fig. 2.6.11), as such details will require the contractor to pierce the forms and provide seals around the items extending beyond the concrete. Repairs will be required after use, adding to the labor, time and materials costs associated with the penetrations. In almost all cases, the protruding items will create obstructions during form removal, reducing efficiency and increasing the risk of additional damage to the formwork.

Fig. 2.6.11: Details requiring formwork surfaces to be penetrated by PT strands and reinforcing bars will mandate labor-intensive removal of forms and consume formwork materials. While the shown penetrations are not on a gang form, they may have prevented the use of such a productivity enhancing form system. (Image courtesy of Ceco Concrete Construction.)

(h) **Define the form removal strength:** Form removal strength is a critical item in achieving a productive formwork schedule, as the ability to rapidly reuse forms reduces the amount of formwork material needed. Vertical formwork is typically removed the morning after the vertical concrete pour. Adequate design strength should be achieved to allow removal of horizontal formwork on the third day after a deck pour (Fig. 2.6.12), allowing the formwork to be repositioned for another pour. As schedules become more demanding, contractors may seek to remove horizontal formwork even sooner—possibly the day after the deck pour—thus requiring earlier concrete strength gain. To improve constructability, the designer should define strength levels adequate for tendon tensioning and/or shoring release, rather than specifying that form removal is allowed at an arbitrary concrete strength level or period. As an example, post-tensioned (PT) anchors require a minimum concrete strength of 3000 psi for strand tensioning. In the construction documents, allow the contractor to proceed accordingly. The designer should also allow construction live loads to be carried by reshores to lower levels of the structure. Reshores are installed after the horizontal formwork has been removed and the floor structure deforms under its own weight (releasing the dead load is essential for reshoring calculations). Reshores should be installed before the end of the day within the bay where shores are removed. In contrast to reshoring, backshores are installed before formwork shoring is removed, so backshoring will not release the dead load to be carried by the horizontal framing. Backshoring is highly problematic, largely because it does not allow the floor structure to deform and carry its own weight. Construction loads therefore accumulate with elevation, which inhibits constructability.

Fig. 2.6.12: Workers remove deck formwork before installing reshores. (Image courtesy of Ceco Concrete Construction.)

(i) **Reduce idle formwork material:** Many projects are multipurpose, requiring multi-phased construction. As a result, they may require multiple formwork systems due to varying shoring heights or structural element dimensional needs. Unfortunately, some formwork material can be idled (Fig. 2.6.13) and therefore be in the way of other trades until needed. Concrete contractors will analyze the cost and time trade-off of demobilizing the idle formwork material and later remobilizing it. These tasks are not inexpensive and can demand valuable resources, including labor and crane availability, so the contractor will evaluate smaller placements using additional construction joints and/or expansion joints (Fig. 2.6.14), thus allowing reduced need for specialized formwork and allowing idle formwork material to be re-engaged sooner.

Fig. 2.6.13: A project "boneyard" of idle formwork. (Image courtesy of Ceco Concrete Construction.)

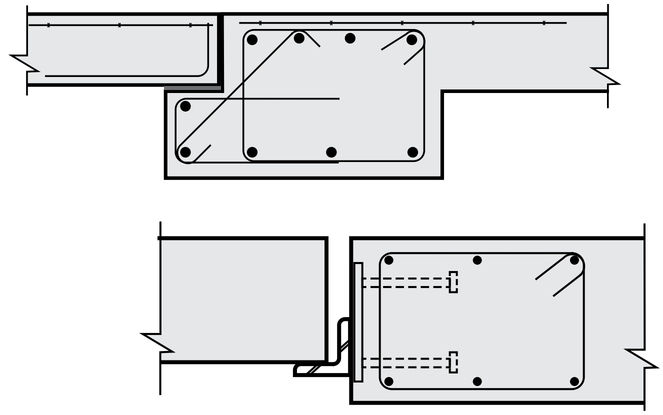


Fig. 2.6.14: Examples of expansion joint details for PT construction. If required to maintain a diaphragm, reinforcing bars with slip connecters can be included and grouted after initial shrinkage is complete.

By permitting unusual conditions to be isolated, designers can aid in improving constructability. For example, if a project has a larger base structure and additional floors with a smaller footprint, the contractor may investigate whether the area comprised of the smaller tower footprint can be isolated within the base structure. Such will allow its construction to proceed at a greater pace while the construction of the base structure continues (Fig. 2.6.15). Likely each will require differing formwork and the isolation will expedite the tower and minimize the quantity of formwork supplied.

Fig. 2.6.15: A project with a tower structure isolated from a base structure. The separation followed a straight column line rather than the radius of the tower. (Image courtesy of Ceco Concrete Construction.)

As another example, a project may have highly shored elevated slabs requiring special formwork, additional time, and additional labor to construct. As in the previous example, the contractor may investigate if the elevated area can be isolated. If so, isolation should make it possible to allow an earlier start, allow a longer duration, or to minimize the formwork material and reuse it with smaller pours. In short, allowing unusual conditions to be isolated will aid in improving constructability.

(j) **Standardize formwork sizes:** Constructability is enhanced when structural details are developed around dimensional industry standards. Although deviating from industry standards leads to customization and thus is costly in materials and time, contractors can usually achieve interesting architectural features while applying dimensional industry standards to structural elements (Fig. 2.6.16).

Fig. 2.6.16: An extreme example of an unusual and expensive column shape. Such features should be limited to structures in which such architectural statements are desired. (Image courtesy of Ceco Concrete Construction.)

Fig. 2.6.17: Examples of concrete column forms: (a) rectangular; and (b) round. (Images courtesy of Conco.)

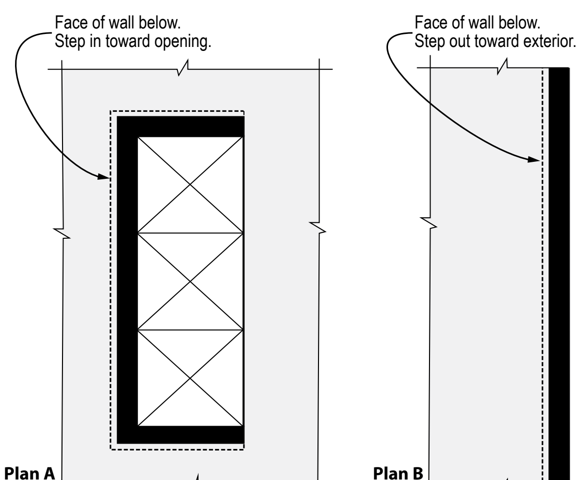


Fig. 2.6.18: Wall faces defining opening edges and exterior of structure are normally held over the building height. Reductions in wall thickness are therefore made by shifting one form face toward an opening or the building exterior.

1. **Rectangular column** (Fig. 2.6.17(a)): Standard rectangular column forms provide sides with 18 to 30 in. dimensions, with intermediate sizes available in 2 in. increments. If a column side exceeds 30 in., formwork pressure will necessitate stronger, stiffer formwork and/or tie rods through the column. If designs call for columns with unusual shapes, the forms will likely be custom-made and costly—designs ensuring multiple uses (at least 30) will help to minimize cost impacts.

2. **Round columns** (Fig. 2.6.17(b)): Standard round column forms are 12 to 36 in. in diameter, with intermediate sizes available in 6 in. increments. Single-use formwork will be fiberboard; multiple-use formwork will be made from fiberglass or steel, with the latter commonly used when the column diameter exceeds 36 in. Unless it is necessary to meet other design features, designers should avoid reducing the column diameter with decreasing load. Consider round columns over rectangular in multilevel towers for constructability. The forms require less onsite storage space and lateral bracing when installed. Further, finished trade interior walls connect easily to round columns, without the tolerance challenges of aligning the face of a rectangular column with the face of an interior wall.

3. **Walls:** Standard wall formwork systems accommodate wall thicknesses ranging from 8 to 18 in., in 2-in. increments. Systems for thicker walls accommodate thickness changes in 6 in. increments. When reducing wall thickness as loads decrease, designers should step-in the wall face toward an opening or building edge, as shown in Fig. 2.6.18.

4. **Beams:** For maximum productivity, designers should strive to standardize beam depths; standard depths range from 4 to 20 in., in 2 in. increments. When a beam side exceeds 20 in., the additional formwork members (studs, walls, and tie rods) will be

required to resist the pressure induced by the fresh concrete (Fig. 2.6.19). The tie rods significantly impact productivity because they must be pushed through the formwork after reinforcing bars and PT strands have been installed in the form. This is a difficult, labor-intensive procedure, requiring workers on both sides of the beam below the slab formwork and another worker above. The three workers must thread each tie rod through the reinforcing and through the sheathing on the opposite beam side form. Designers are thus encouraged to limit beam side depth to 20 in. and use wide, shallow beams. However, if form depths must exceed 20 in., designers should limit the number of size changes, as contractors will seek to panelize the deeper beam side forms and minimize waste through multiple reuses.

2.6.19: Photos of forms with beam sides connecting beam bottoms with slab soffits: (a) form depths of 20 in. or less allow form sides to carry concrete pressures with minimal members (photo courtesy of Ceco); and (b) form depths exceeding 20 in. necessitate studs, wales, and tie rods. (Image courtesy of Hensel Phelps.)

Post-tensioned concrete parking structures are typically constructed using beams with 60 ft spans, constructed using single-piece steel beam forms (refer to Fig. 2.6.3(b) and Fig. 2.6.20). The sides of the steel forms will typically have a 1 in. total draft on each side

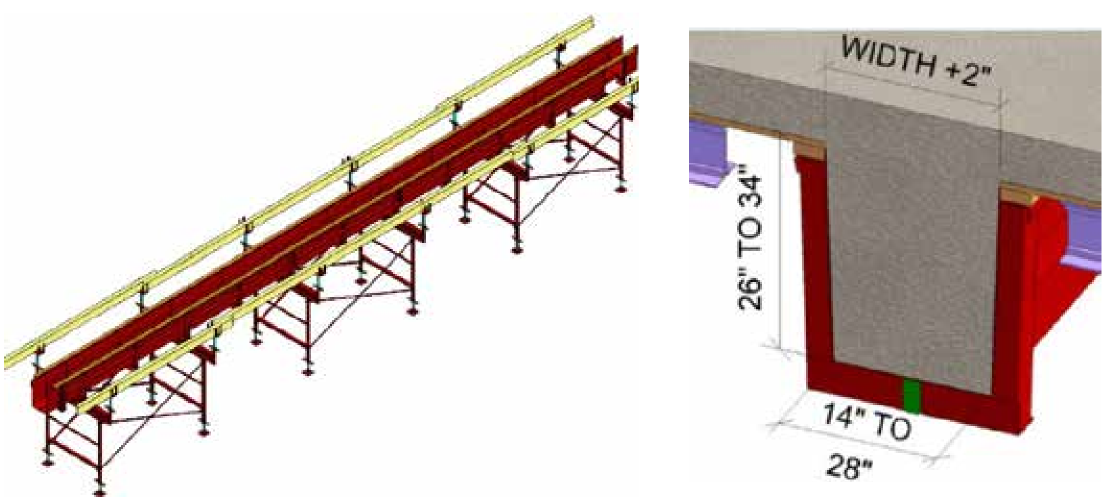


Fig. 2.6.20: Single-piece forms are commonly used to construct repetitive long-span beams in parking structures. The form sides of such systems can resist fresh concrete pressures without the need for tie rods. (Image courtesy of Ceco Concrete Construction.)

to allow the form to be readily removed. Standard widths range from 14 to 28 in., in 2 in. increments, and standard side depths range from 26 to 34 in., in 2 in. increments.

5. **Pan slab construction**: Pan systems provide an efficient beam/slab construction system that minimizes concrete while creating beam ribs that enable reinforcement to be effective with industry-standard pan depths of 14, 16, 20, and 24 in. (Fig. 2.6.21 and 2.6.22). Pan construction has advantages of long spans, efficient use of concrete, structural stiffness, and heavy design live loads. Standardization of void sizes and a minimum of three to five steel pan formwork reuses are necessary to capture the productivity potential. For additional information, refer to the Pan Construction Resources links on the Ceco Concrete Construction Pan Construction Resources website. Overlapping steel pans are typically installed on a shored plyform deck, so the greatest efficiencies are gained by maintaining consistent beam depths throughout the framed area (refer to Section A in Fig. 2.6.23). Added benefits of a uniform soffit elevation include reduced installation costs for HVAC, plumbing, electrical, interior partitions, and ceilings.

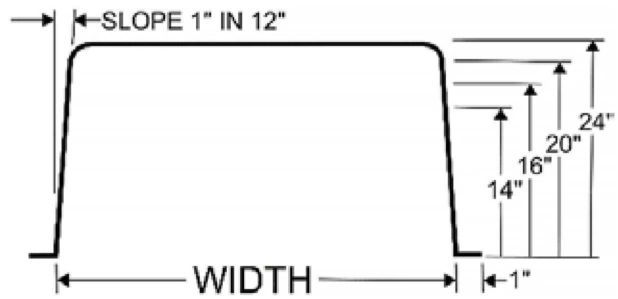


Fig. 2.6.21: Pan systems are available in widths of 20, 30, 53, and 66 in. The beam width can be varied by adjusting the gap between pans. (Illustration courtesy of Ceco Concrete Construction.)

Fig. 2.6.22: Examples of pan system construction. (Images courtesy of Ceco Concrete Construction.)

(k) **Standardize piers, pile/caisson caps, spread footings, and grade beams:** Concrete contractors will seek to panelize formwork for foundation concrete. To do so, minimize the number of pier sizes, pile caps, spread footings, and grade beams. Better yet, standardize the depth and align the structural elements to minimize layout and installation error (Fig. 2.6.24). Foundation layout is often difficult, with limited access and continually changing conditions during excavation operations. A rule of thumb is that if the

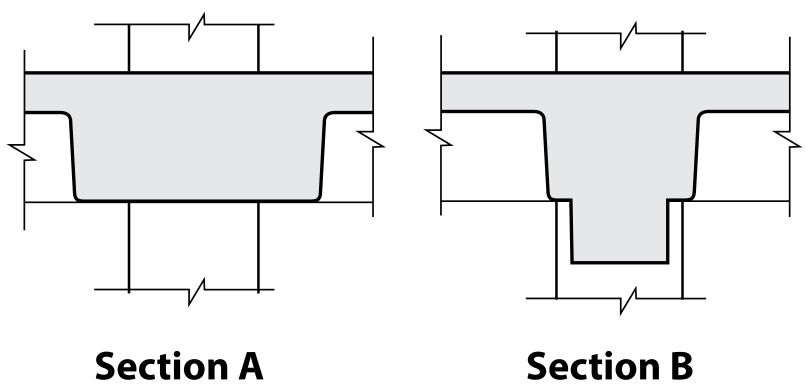


Fig. 2.6.23: Pan systems are most efficiently applied when the floor framing has a consistent soffit elevation. Interior and exterior beams and girders should match the pan depth plus slab thickness whenever possible (Section A). If girders are designed with greater depth, the shored deck supporting the pans must be interrupted and the extended depth requires additional formwork for the sides, soffit, and shoring (Section B).

gap between spread footings (pile caps, too) is less than one-third of the footing size, then design the footings to take advantage of a continuous footing or a mat footing. Large mats have many design and constructability advantages. Grade beams are unproductive and should be eliminated if possible. If necessary, standardize and match the depth of the supporting footing or pile/caisson cap. If one end has a deeper footing than the opposite, then slope the bottom between footings.

Fig. 2.6.24: While designing footings to have matching depth and alignment aids in constructability, even greater constructability may be achieved by replacing closely spaced footings with a continuous footing. (Image courtesy of Ceco Concrete Construction.)

(l) **Standardize stairs and steps:** Standardizing stair lifts and minimizing steps allows the concrete contractor to customize and standardize formwork (Fig. 2.6.25(a)), or possibly use precast stair elements (Fig. 2.6.25(b)) if justified by sufficient repetition. Designers should not focus purely on size or dimensional minimums, as contractors need ACI construction tolerances and flexibility to achieve Americans with Disabilities Act (ADA) requirements. Consider both standards during design to help minimize field error, dimensional and code conflicts, and unnecessary rework and change orders. To meet ADA surface accessibility requirements as well as accommodate for the accuracy of the inspection tool and the effects of local surface roughness, the ASCC Technical Committee recommends that designers specify maximum slopes that are slightly less than the ADA requirements (refer to **Designing for Constructability— ADA Surface Accessibility**).

Fig. 2.6.25: Construction of concrete stairs: (a) cast-in-place concrete; and (b) precast concrete. (Image courtesy of Ceco Concrete Construction.)

(m) **Story heights:** It is understood by concrete contractors that designers must increase story heights in areas such as accessways for service vehicles, lobbies, and mechanical equipment rooms. To maximize constructability, however, designers should seek to maintain consistent story heights, as concrete contractors will seek to standardize shoring with minimal adjustments and thereby maximize productivity and minimize the risk of field errors (refer to examples in Fig. 2.6.26). If spacing between floors is consistent, the same vertical shoring material can be recycled from one level to the next. Wall forms and column forms are not easily adjusted for story height changes greater than 12 in., however, so larger changes in story height require alternative solutions. Often, contractors will design and assemble wall and column formwork as needed for the tallest story and adapt concrete placements to accommodate the shorter stories. However, this approach can become problematic.

Fig. 2.6.26: Examples of high shoring. ((a) Image courtesy of Ceco Concrete Construction. (b) Image courtesy of Conco.)

Another contractor choice is to design vertical formwork for the typical story height and use two lifts (double-lift) or multiple lifts to place vertical elements in taller stories (Fig. 2.6.27). Double lifting of the form allows the reuse of the typical wall formwork by creating a horizontal construction joint mid-height of a taller wall (the reinforcement extends the full height of the wall). After the lower pour is made, the wall formwork is lifted and secured to achieve a second pour to the desired wall height. This solution maintains use of standard modules while requiring only a supply of different formwork shores.

Fig. 2.6.27: Examples of multiple-lift formwork applications for tall story heights: (a) double-lift column construction. (Image courtesy of Ceco Concrete Construction); double-lift wall construction. (Image courtesy of Related); and (c) five-lift column construction using a single column form. (Image courtesy of Ceco Concrete Construction.)

(n) **Avoid warping formwork to achieve two-way slopes, drainage, and camber:** Architects may seek elegant structural shells and arches, and these are achievable using bespoke formwork (for example, Fig. 2.6.16). However, such elements are outside the scope of typical construction projects and are not the focus of this chapter on formwork constructability. Much of this chapter focuses on formwork for floor framing, which is typically comprised of members that are straight, lie in a single plane, and efficiently collect and transfer fresh concrete loads to shoring posts (Fig. 2.6.28). These formwork systems are not designed to be warped or be configured as two intersecting planes, so designers should avoid designs calling for warping or two-way slopes of the deck soffit to achieve two-way sloping of an elevated deck (Fig. 2.6.29 and Fig. 2.6.30(a)). A constructable alternative is achieved using one-way sloping of the soffit combined with localized variations in the deck thickness (Fig. 2.6.30(b) and (c)).

Fig. 2.6.28: Straight-soffit formwork elements are used to achieve a one-way slope transition with high shoring. While the formwork for such a transition is complex, it is more constructable than the formwork required to create a two-way slope or a warped slab. (Image courtesy of Hensel Phelps.)

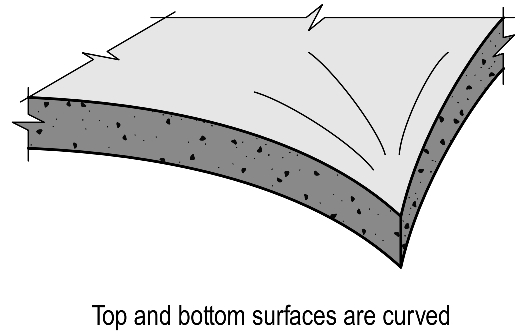


Fig. 2.6.29: Warping of top and bottom surfaces of a slab is highly problematic. (Image courtesy of Ceco Concrete Construction.)

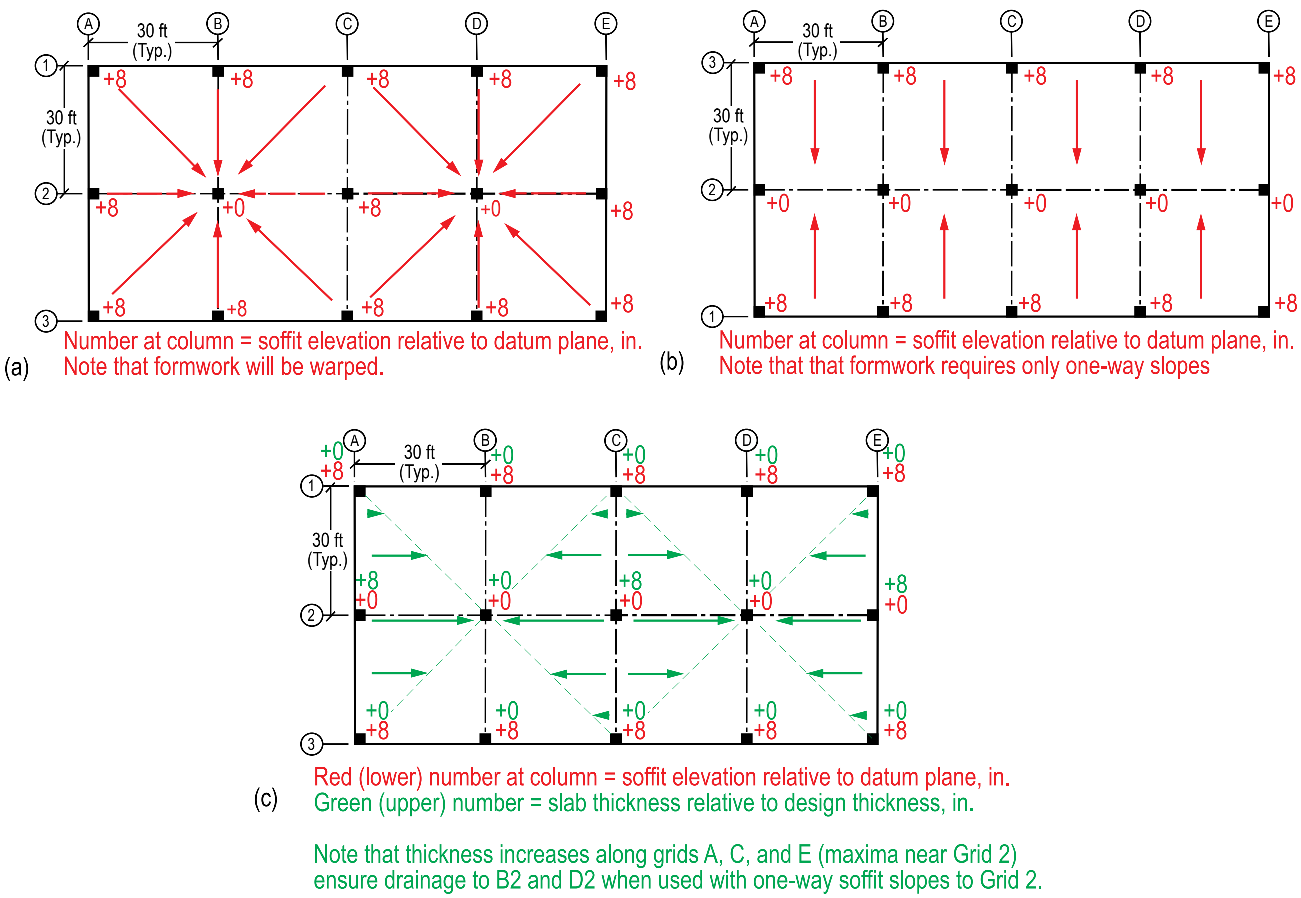


Fig. 2.6.30: Schematic illustrations of an eight-bay roof plan with two interior drain points: (a) two-way sloping of the soffit creates constructability challenges because it requires warping of formwork; (b) one-way sloping of the soffit allows the formwork elements to remain straight; and (c) localized increases in slab thickness (or crickets formed using a topping course or added insulation) can be combined with one-way sloping of the soffit to enable two-way slopes.

Warping top and bottom surfaces (Fig. 2.6.29) is the most extreme impediment to productivity, as it requires intricate, expensive carpentry that must be precisely installed. Further, it is difficult to place and finish concrete with curved top and bottom surfaces, as adjacent beam side, column, and wall elevations become variable and are therefore difficult to accurately fabricate. Most constructable solutions have slopes for drainage and camber in a single direction or plane. An even better solution is to maintain a level slab soffit elevation and modify the thickness of the slab in a single direction to achieve the desired drainage while maximizing construction productivity.

Consider the conditions where camber is needed. A nonprestressed podium slab that will support many levels of wood framing presents a particular condition that requires significant camber to address long-term creep. But also consider the limitations of camber. Camber is a poor solution, for example, when standard span-to-slab-depth minimums are exceeded (Tables 2.6.1 through 2.6.4). In most cases, camber should be avoided as it adds complexity to the formwork and concrete placing operations. Further, camber will invalidate FF/FL testing and flatness expectations. If required, one-way camber of a mildly reinforced slab can be achieved with best results when the camber requirement is the same in all bays. Camber requirements should be a minimum of 1/2 in., with additional camber in 1/2 in. increments. Using topping slabs to achieve greater slopes and drainage are another recommended option. Noting that the allowable tolerance for form elevation is ±3/4 in., it makes little sense to overthink a detailed customized camber plan for each bay. Simplify one-way camber, if necessary, for better constructability. For additional information on deflection limits for nonprestressed slabs, refer to "**Span-Depth Ratios for One-Way Members Based on ACI 318 Deflection Limits**," published in the *ACI Structural Journal*, Sept.-Oct. 2009. While ACI 318-19(22) allows designers to exceed the limits in Tables 2.6.1 through 2.6.4 by predicting deflection through calculations, constructability invariably suffers when the limits are exceeded.

Table 2.6.1: Minimum thickness of nonprestressed one-way slabs comprised of normalweight concrete per ACI 318-19(22) Section 7.3.1.1

Support condition	Minimum slab thickness		
	f_y = 60,000 psi	f_y = 80,000 psi	f_y = 100,000 psi
Simply supported	$\ell/20$	$1.2\ell/20$	$1.4\ell/20$
One end continuous	$\ell/24$	$1.2\ell/24$	$1.4\ell/24$
Both ends continuous	$\ell/28$	$1.2\ell/28$	$1.4\ell/28$
Cantilever	$\ell/10$	$1.2\ell/10$	$1.4\ell/10$

Note: ℓ is span; f_y is slab reinforcement yield strength.

Table 2.6.2: Maximum span of nonprestressed one-way slabs comprising Grade 60 reinforcement and normalweight concrete, based on Table 2.6.1.

Slab thickness, in. (mm)	Simply supported, ft in. (m)	One end continuous, ft in. (m)	Both ends continuous, ft in. (m)	Cantilever, ft in. (m)
5 (125)	8’ 4” (2.5)	10’ 0” (3.0)	11’ 8” (3.5)	4’ 2” (1.2)
6 (150)	10’ 0” (3.0)	12’ 0” (3.6)	14’ 0” (4.2)	5’ 0” (1.5)
7 (180)	11’ 8” (3.6)	14’ 0” (4.3)	16’ 4” (5.0)	5’ 10” (1.8)
8 (200)	13’ 4” (4.0)	16’ 0“ (4.8)	18’ 0” (5.6)	6’ 8” (2.0)
9 (230)	15’ 0” (4.6)	18’ 0” (5.5)	21’ 0” (6.4)	7’ 9” (2.3)
10 (250)	16’ 8” (5.0)	20’ 0” (6.0)	23’ 4” (7.0)	8’ 4” (2.5)
11 (280)	18’ 4” (5.6)	22’ 0” (6.7)	25’ 8” (7.8)	9’ 2” (2.8)

Note: ‘ = ft, “ = in.

Table 2.6.3: Minimum thickness of nonprestressed two-way slabs without interior beams or drop panels and comprised of normalweight concrete, per ACI 318-19(22) Section 8.3.1.1

f_y, psi	Exterior panels		Interior panels
	Without edge beams	With edge beams	
60,000	ℓn/30	ℓn/33	ℓn/33
80,000	ℓn/27	ℓn/30	ℓn/30

Note: ℓn is clear span; f_y is slab reinforcement yield strength.

Table 2.6.4: Maximum span of nonprestressed two-way slabs without interior beams or drop panels and comprised of Grade 60 reinforcement and normalweight concrete, based on Table 2.6.3.

Slab thickness, in. (mm)	Exterior panels		Interior panels, ft in. (m)
	Without edge beams, ft in. (m)	With edge beams, ft in. (m)	
6 (150)	15’ 0” (4.5)	16’ 6” (4.9)	16’ 6” (4.9)
7 (180)	17’ 6” (5.4)	19’ 3” (5.9)	19’ 3” (5.9)
8 (200)	20’ 0” (6,0)	22’ 0” (6.6)	22’ 0” (6.6)
9 (230)	22’ 6” (6.9)	24’ 9” (7.6)	24’ 9” (7.6)
10 (250)	25’ 0” (7.5)	27’ 6” (8.2)	27’ 6” (8.2)
11 (280)	27’ 6” (8.4)	30’ 3” (9.2)	30’ 3” (9.2)
12 (300)	30’ 0” (9.0)	33’ 0” (9.9)	33’ 0” (9.9)

Note: ’ = ft, ” = in.

(o) **Avoid top-of-slab transitions, slab soffit offsets, and formwork penetrations:** Top-of-slab transitions are unproductive and problematic to construct, largely because it is difficult to provide anchorage for the required formwork (Fig. 2.6.31(a)). Craft workers will inevitably step on the formwork and dislodge or dislocate portions during concrete placement, resulting in rework. Further, if large transitions are required (Fig. 2.6.31(b)), the upper concrete mass will exert uplift pressures in the depressed areas, making it difficult to achieve the required finish elevation. If depressions are required for recessed flooring, designers should consider depressing a larger area and adding fill where required to achieve the desired upper elevation.

Fig. 2.6.31: Examples of problematic slab transitions: (a) the forms at this transition are not braced, increasing the risk of displacement during the concrete placement; and (b) this large transition will create high uplift pressures in the lower concrete surface, making it difficult to achieve the required surface finish. (Images courtesy of Ceco Concrete Construction.)

In many cases, it is more economical to add concrete to the top slab surface after it has hardened (Fig. 2.6.32(a)) rather than to maintain constant slab thickness through an offset in the slab soffit (Fig. 2.6.32(b)). For steps of 3 in. or less, constructability will be enhanced if the topping is non-structural. In general, offsets in the slab soffit elevation disrupt formwork placement, requiring additional labor, more cutting of material, and additional waste (Fig. 2.6.33 and 2.6.34).

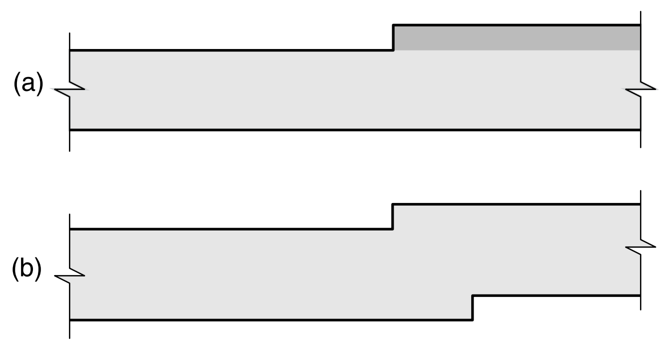


Fig. 2.6.32: Examples of slab transitions: (a) transition created by placement of a topping course; and (b) transition created using offsets at both the top surface and soffit of a slab.

Fig. 2.6.33: Slab soffit offsets require interruption of the formwork framing, forcing the need for additional shores, labor, and time. (Image courtesy of Ceco Concrete Construction.)

Fig. 2.6.34: A drop panel has been formed and is awaiting reinforcement installation. Better constructability is achieved using shear studs in lieu of a drop panel (refer to Section 2.7(h)). (Image courtesy of Ceco Concrete Construction.)

Deeper transitions are best achieved when the top surface and soffit of the slab transition equally (Fig. 2.6.35(a)) or they are located at the side of a beam or girder (Fig. 2.6.35(b)). In both cases, the floating form can be properly anchored with a tie between the vertical sides.

Formwork penetrations for reinforcement, ductwork, or plumbing should be avoided (Fig. 2.6.36). Although formwork must be penetrated by strands at PT anchors, specifications should allow bar couplers to avoid penetrations for reinforcing bars. For mechanical or plumbing fixtures, consider using oversized sleeve blockouts. If possible, standardize the blockout size and use circular blockouts when the fixture size is less than 24 in. diameter.

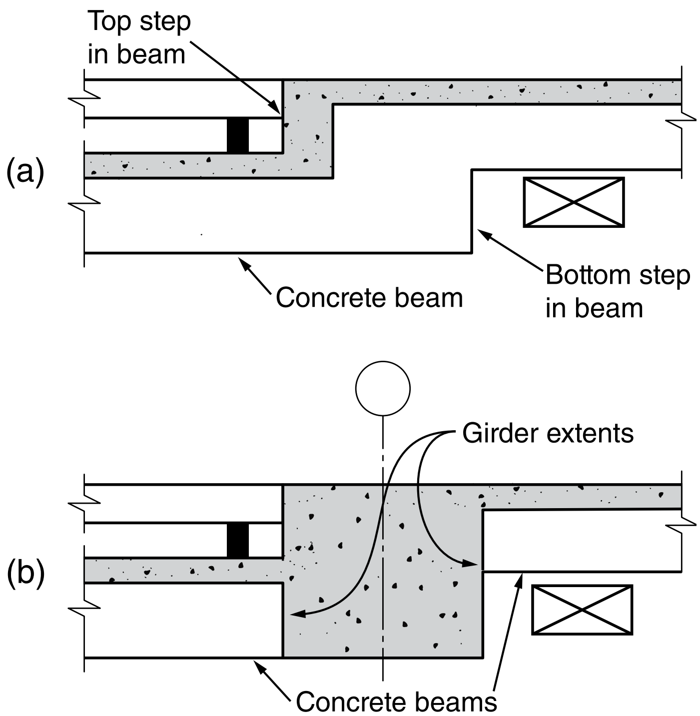


Fig. 2.6.35: Deep transitions in slab elevations: (a) equal transition depths should be provided for the top and soffit elevations; and (b) transitions should be located at the side of a beam or girder.

Fig. 2.6.36: A progress photo showing a wall with two layers of reinforcement penetrating the vertical formwork at a construction joint. Such joints are labor- and time-intensive to form and remove, so contractors seek to minimize such construction joints and reinforcing penetrations to improve constructability. (Image courtesy of Hensel Phelps.)

(p) **Minimize formwork shoring heights:** Today's formwork manufacturers capitalize on efficient shoring designs. Productivity is optimum for shoring heights ranging from 6 to 12 ft and steadily decreases with height from 12 to 20 ft (Fig. 2.6.37). Above 20 ft, productivity decreases at an even greater rate, as at that height, shores are no longer a solution and shoring towers are necessary. With sufficient uses, however, it is possible for higher deck formwork to comprise a table panel that can be designed to reduce the effect of the shoring height on productivity. Designers may consider using precast concrete elements

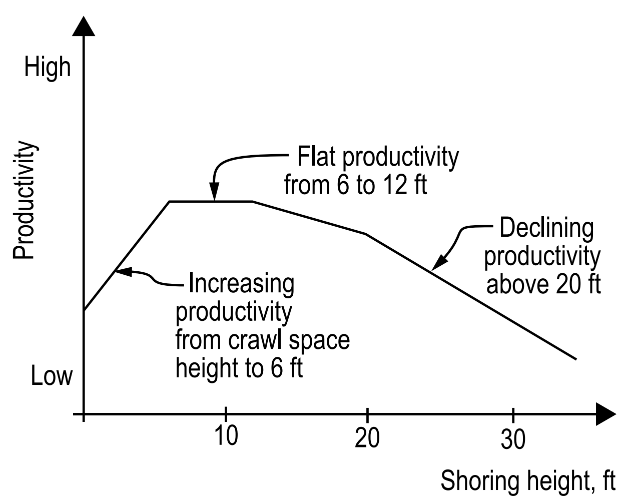


Fig. 2.6.37: Schematic illustration of the effect of shoring height on construction productivity.

for constructing floors. Either solution will assist in reducing the construction schedule, thus maintaining optimum productivity. While the focus here is productivity, it should be noted that production (area of slab construction per day) drops similarly to the productivity. Production can drop by 40% as the shoring height increases from 12 to 20 ft and more dramatically when the shoring height increases above 20 ft.

(q) **Mitigate shoring loads:** Some design features can inadvertently affect productivity by creating special shoring conditions. A transfer girder in an elevated floor, for example, can represent a large dead load requiring substantial shoring and reshoring (Fig. 2.6.38). A good solution is to design a beam to support the dead load of the transfer girder (Fig. 2.6.39).

Fig 2.6.38: This project included an upper-level floor with a large dead load. Seven levels of reshores were needed to support the placed concrete. The reshores delayed finish trades in the affected levels and extended the overall construction schedule until sufficient concrete strength was attained on the freshly placed level to allow removal of shoring. (Image courtesy of Mary Bordner Tanck.)

Fig. 2.6.39: Reinforcement and formwork placement for a deep transfer girder. The wide reinforcing cage below was designed as the reinforcing cage for a beam that will support the transfer girder and its formwork during placement, thus avoiding the need for shoring to support the full weight of the deep girder. (Image courtesy of Ceco Concrete Construction.)

Pour strips are required to accommodate cable tensioning jacks for post-tensioning of slabs. Pour strips have a minimum width of 3 ft, and the slabs bordering a pour strip may be cantilevers that are required to be fully shored (unreleased) until the pour strip concrete has been placed and reaches full strength (Fig. 2.6.40). Further, project specifications may require pour strips to remain open for long durations (45 to 90 days) to minimize cracking associated with restrained shrinkage. If backshoring (Fig. 2.6.41) is needed to carry the dead loads of the slab cantilevers, the extended durations required for the slabs to be unreleased can create significant delays, as the shores obstruct the work of finish trades on the affected floors. This is especially true when the pour strips are stacked above one another in the same bay of a multi-story structure.

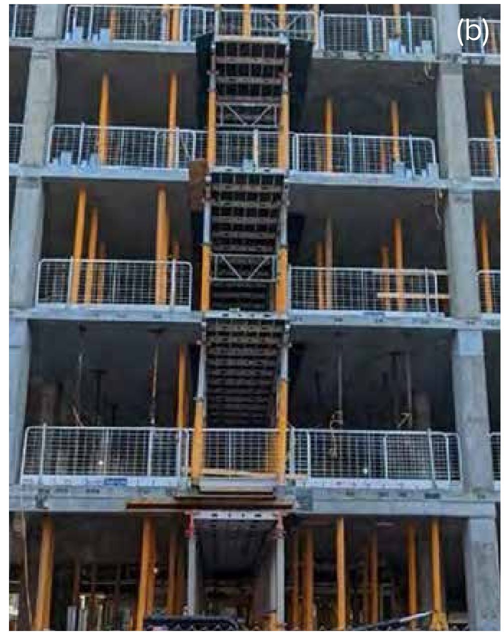


Fig. 2.6.40: Shores at pour strips create obstructions that will affect the productivity of all trades: (a) shores allow only narrow passageways with bridging over the open pour strips; and (b) such obstructions exist over multiple floors. (Images courtesy of PS=0.)

Shoring will also affect the concrete contractor's construction sequence. As shown in Fig. 2.6.41(a) and (b), shores take on additional dead load as additional levels are constructed. In many cases, the contractor must release the shoring in the affected bay from the top of the structure down after the project has been topped out and shrinkage durations have been achieved.

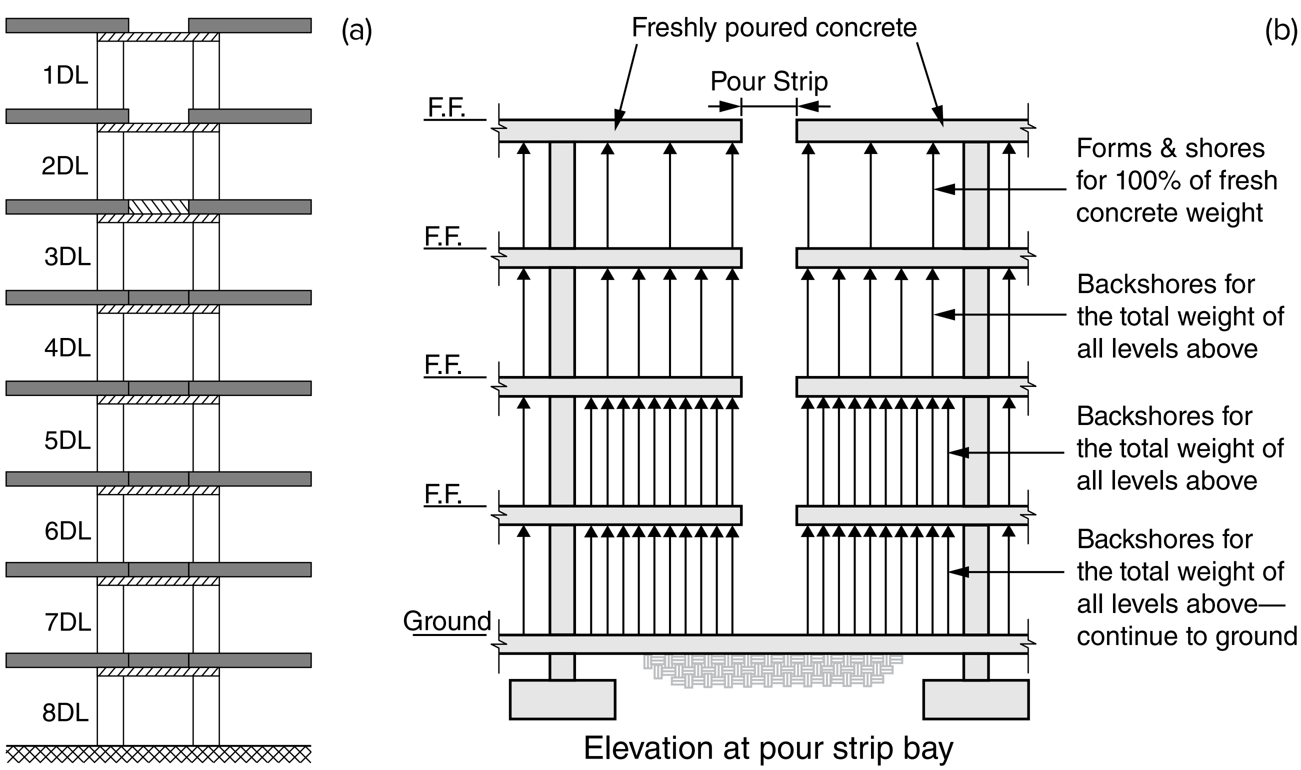
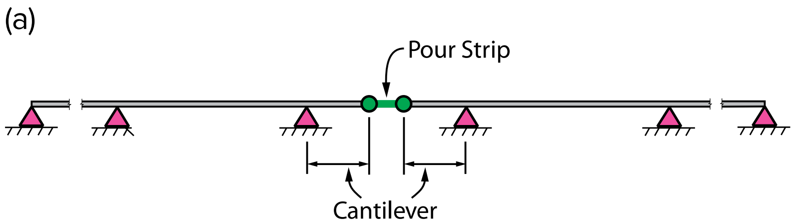


Fig. 2.6.41: Backshores supporting pour strips: (a) loads increase with every additional level (courtesy of Ceco Concrete Construction); and (b) the density of backshores increases with every additional level. (Image courtesy of the Post-Tensioning Institute.)

To avoid this condition, floors can be designed with post-tensioning such that the slabs adjoining the pour strip behave as cantilevers supporting their self-weight (Fig. 2.6.42). While achieving a self-supporting cantilever may require widening of the pour strip or offsetting the opening in the bay, this solution will allow shoring to be released earlier. Further, shoring loads can be reduced by use of reshoring to carry construction loads (Fig. 2.6. 40(b)) rather than backshoring (Fig. 2.6.41(b)). After the pour strip is shored and poured, reshores may be unnecessary unless the pour strip is significantly widened for the cantilevered slab design.



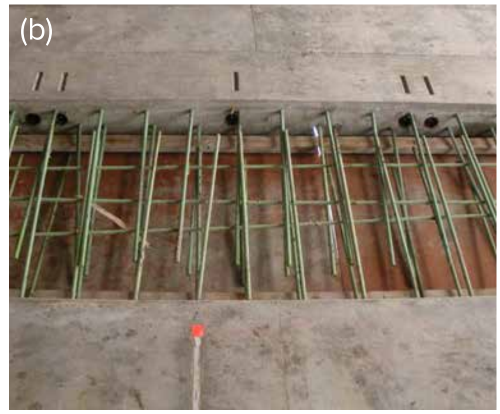


Fig. 2.6.42: Designing a pour strip as a simple span supported by PT cantilevers can help avoid the need for backshoring: (a) schematic model of a strip; and (b) the PT cantilevers are self-supporting. (Image courtesy of AMSYSCO.)

Designers should also be open to other design alternatives such as relocating the pour strips by staggering bays or using shear couplers that allow shrinkage movement without the need for an open pour strip. For additional insights, refer to "**Pour Strips and Constructability**," in the April 2014 edition of *Structure*. Using post-tensioning in beams and girders or transfer girders can also be especially helpful. Stage post-tensioning (refer to Slater (1975), "**Stage post-tensioning: versatile and economic construction technique**"), for example, can enhance constructability by reducing the need for shoring, thus leaving open areas for other trades and shortening construction time.

When a floor design includes PT slabs, beams, and girders, designers and contractors will consider the effects of sequencing of tendon tensioning (Fig. 2.6.43). When the slabs are fully tensioned prior to the beam tensioning (Fig. 2.6.43(a)), all the slab dead load is transferred to the beams, so shoring for the beam formwork must be sufficient to pick up the slab dead loads as well as the beam dead load (Fig. 2.6.43(b)). While this loading is effective for only a short period of time until the beam cables are tensioned, the shoring load below the beam has been concentrated. If the beam frames into a PT girder, the shoring demand at that location will further be concentrated if the subsequent PT stage is not managed correctly. Thus, redundant shoring and reshoring is required as the loading is relocated due to the cable tensioning sequence.

A better solution is to consider reinforcing the girders for a staged tensioning sequence, allowing girder capacity to be established for the beam loading prior to tensioning of the beam (Fig. 2.6.43(c)). The staged tensioning sequence of the girder will then allow further increases in girder capacity once the slab and beam loads are fully supported by the girder.

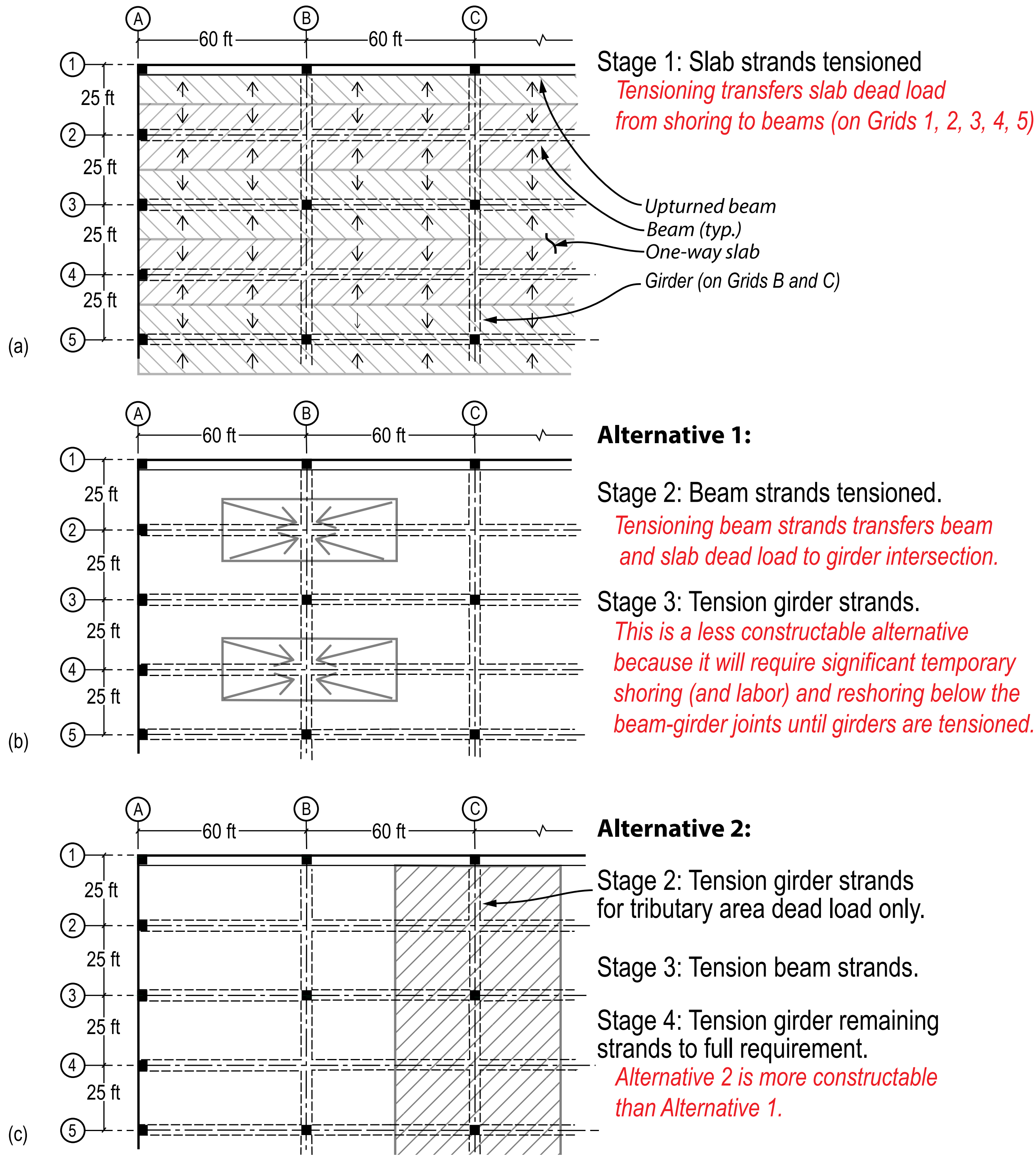


Fig. 2.6.43: An example of stage post-tensioning: (a) Stage 1, tensioning of strands in the slab will unload the shores under the slab and add to the shoring loads under the beams; (b) if beam strands are tensioned in Stage 2, the slab and beam loads will be transferred to supporting girders, thus adding significantly to the shoring loads at the intersections of beams and girders; and (c) if instead the girder strands are tensioned in Stage 2, the high local shoring loads at the beam intersections can be avoided. For additional information, refer to "Reshoring and Early-Age Building Behavior," an on-demand course available through ACI University.

Many projects will have heavy floor structures supporting high dead loads (for example, floors with mechanical equipment or swimming pools; refer to Fig. 2.6.44 and 2.6.45). If a heavy floor structure is above several lightly loaded floors, six to eight levels of reshores may be required to provide temporary support for the heavy structure during curing. The additional reshoring will impede the work of finish trades, including electrical, mechanical, and plumbing work. The additional levels of reshoring will therefore push out the project completion several weeks, severely reducing productivity. A more constructable solution is to increase the design loads on the lighter floors below to provide capacity that can allow the contractor to reduce reshoring to only three levels. If this approach is planned during the design phase, the overall cost and schedule is reduced.

Fig. 2.6.44: A roof structure with a swimming pool, green roof, and mechanical equipment. High dead loads such as these may require a heavy structure that must be supported by multiple levels of reshores. (Image courtesy of Ceco Concrete Construction.)

Fig. 2.6.45: A floor required to support mechanical equipment, a swimming pool, or to transfer loads to create a column-free space will have a high dead load, requiring a high quantity of reshores that will delay the work of interior trades (photo courtesy of Conco).

The contractor's engineers will seek to use the full carrying capacity of the structure during construction for support of shoring, reshoring, and construction equipment. This carrying capacity is often more than the design strength. Limiting the construction loads to the design strength will slow construction and reduce constructability, so it's important to work with the contractor to determine the total carrying capacity for support of construction loads (**Guide for Shoring/Reshoring of Concrete Multistory Buildings**). By improving constructability, all outcomes are productivity gains for the contractor and therefore scheduling gains for the owner.

(r) **Consider long-term deflection of floor structures:** In many cases, the greatest gravity loads a project will endure are the short-term construction loads imposed during slab placements. The sum of the fresh concrete weight (an 8 in. slab [200 mm], for example, weighs 100 lb/ft^2 [4.8 kPa]), construction loads (typically, 50 lb/ft^2 [2.4 kPa]), and formwork load (approximately 10 lb/ft^2 [0.5 kPa]) will exceed the design live load of a partially cured structure supporting the shoring. Contractors will install reshores on levels below the shoring level to share these construction loads to additional levels. They will seek to minimize the number of levels and density of reshores by leveraging the stiffness of several levels. The loaded slabs may crack. Although the structural capacity is not reduced if a slab cracks, the stiffness will decrease, and long-term deflections may double or triple the initial deflection (refer to Table 2.6.5). If this is a concern, the designer should specify minimum requirements on reshoring capacity, type, and spacing (density). Condominiums with long-span floors or projects such as hospitals that have functional requirements affected by deflections are examples where this additional step may be taken. Designers may also anticipate and allow for the contractor to use a leveling compound after removal of reshores in areas where deflection is the greatest and requires remediation.

For additional information on this topic, refer to **Estimating Two-Way Slab Deflections**, **Designing Shoring/Reshoring Schedules for a Fast-Track Project**, and **Statistical Evaluation of Minimum Thickness Provisions for Slab Deflection Control**.

Table 2.6.5: Recommended multipliers to be applied the calculated immediate deflection for two-way slabs (for more information and citations, refer to ACI 435R-20, "Report on Deflection of Nonprestressed Concrete Structures"). Note that ACI 318 has the lowest factor for long-term effects.

Source	Immediate	Long term		Total
		Creep	Shrinkage	
Sbarounis (1984)	1.0	2.8	1.2	5.0
Branson (1977)	1.0	2.0	1.0	4.0
Graham and Scanlon (1986)	1.0	2.0	2.0	5.0
Hossain et al. (2011)	1.0	3.0		4.0
ACI 318	1.0	2.0		3.0

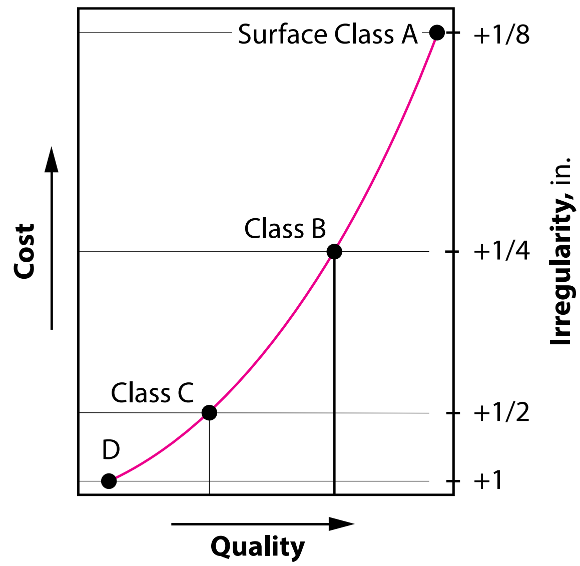
Note: Refer to ACI 435R-20 for source citations

(s) **Reduce reinforcement congestion to improve productivity:** The impact of reinforcement congestion on formwork is often overlooked, especially in locations such as the boundary elements of shear walls, where reinforcement can be densely packed. Many wall forms require a 1.5 in. diameter tie rod within the first 5 ft of a wall end or corner, as these rods may carry as much as 60,000 lb in tension to resist the pressure of the fresh concrete. Designers should strive to provide enough space between bars to allow reinforcing to be installed and adjusted to accommodate form ties (Fig. 2.6.46). While using self-consolidating concrete

Fig. 2.6.46: High-density wall reinforcing creates challenges for workers. Wall reinforcing must allow sufficient space between bars to accommodate form ties. (First image courtesy of Conco; second image courtesy of Ceco Concrete Construction.)

(SCC) can help in achieving consolidation despite reinforcing congestion, it can also add to contractor's constructability challenge by producing significantly higher form pressures than more standard concrete mixtures. The increased pressure results in an increased need for large diameter form ties or reduced tie spacing. Either will require additional space between the reinforcing bars.

(t) **Allow maximum formwork tolerance and formwork offsets possible:** Formwork gang panel weights are large and can reach 10,000 lb. Section 4.8.3 of **ACI 117-10** defines four classes of formed surfaces, with the classes based on the size of allowed irregularities. Classes A and B surfaces may have only 1/8 or 1/4 in. abrupt offsets (Fig. 2.6.47). Specifying such small offset tolerances will reduce the productivity of crews placing forms of this magnitude. **ACI PRC-347.3-13(21), "Guide to Formed Concrete Surfaces,"** recommends that surfaces that are not critical or visible after completion should be specified to have Class C or D surfaces, allowing formed surfaces to have 1/2 or 1 in. offsets.



An abrupt surface irregularity is measured within 1 in. of the offset.

A gradual surface irregularity is the maximum gap between the concrete and a 5 ft straightedge.

Fig. 2.6.47: A schematic illustration of the cost impact of tightened tolerances on formed surface offsets.

(u) **Pre-mobilization time for formwork planning and assembly:** Project owners will realize the greatest benefits when the concrete contractor is authorized to initiate pre-mobilization formwork design, assembly drawings, and formwork assembly during early contractor-designer collaborations. In addition to helping to avoid constructability problems in the construction documents, this authorization will minimize time delays associated with mobilization after the site is ready. A concrete contractor will seek to create a field assembly line process, rather than a piece-meal process, and these efforts will be enhanced by agreeing to a contract at least 3 to 6 months (depending on project size and complexity) prior to mobilization.

(v) Cantilevered balconies: Commonly featured on residential structures, cantilevered balconies can lead to conflicts amongst stakeholders—not only during construction but also during service. While forming the cantilevered balcony soffit is a relatively straightforward task, ensuring adequate slope of the balcony surface can be problematic. Cantilevered balconies are generally extensions of the interior slab, and the slab's PT cables are extended to and anchor at the free end of the cantilever. The top surface of the balcony steps down at the building exterior, and the balcony will be constructed to slope away from the building. Unfortunately, eccentricity in the strand profile can cause the balcony to curl upward after tensioning, defeating the slope, and the depression at the balcony door may be insufficient to prevent water migration. Designers are encouraged to pay special attention to the behavior and drainage of cantilevered balconies. Refer to, for example, Suprenant, B.A., "**Understanding Balcony Drainage**," *Concrete International*, Jan. 2004, pp 84-87; and **Minimum Concrete Cover for Balconies with PT Cables**.

These formwork constructability tips do not ask the designer to assume the role of a formwork planner, nor do they handcuff the designer to formwork considerations. While awareness of these practical formwork considerations is no substitute for design collaboration, a basic understanding of formwork logic may help a designer to capture productivity gains while also achieving the aesthetics, quality, and functional requirements required by the owner. Other relevant references include **ACI SP-4, *Formwork for Concrete*,** and **ACI PRC-347-14(21), "Guide to Formwork for Concrete."**

2.7 REINFORCEMENT LOGIC

Fabrication and installation of reinforcement is a labor-intensive process in concrete construction. A constructability strategy for designers that increases labor productivity and reduces time is prudent to improve value to project owners. **ACI 318-19** states, "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." Designers should look for reinforcement clashes, whether by reviewing typical details and bar schedules in two-dimensional (2-D) construction documents or using clash detection algorithms in three-dimensional (3-D) models of the structure. Primary focus should be on beam-column intersections. Designers should provide as much placement tolerance as possible and consider increasing concrete cover in shear walls to 2 in. to improve productivity. A red flag of constructability concern should be raised when reinforcement density exceeds 400 lb/yd^3 of concrete (Fig. 2.7.1). A 4-in. slump concrete with 3/4 in. aggregate, for example, will not flow easily through a 2 in. space between bars, although ACI 318 allows 3/4 in. aggregate when the clear spacing between No. 8 bars and smaller is only 1 in. The challenge increases with multiple layers of reinforcing bar. Small bar spacing also limits the effective use of vibrators, as contractors typically use vibrators with heads that are 2-1/2 in. in diameter. If head diameter size must be reduced, its radius of influence will also be reduced—more time will be required to consolidate the concrete.

Fig. 2.7.1: The reinforcement in this member approached 800 lb/yd^3 and clearly presented a constructability challenge. (Image from "Reinforcement Congestion in Cast-in-Place Concrete," Concrete International, *December 2022 (ascconline.org).)*

ACI 309R-05, Section 8.1, recommends that designers communicate with the contractor during early structural design. This will allow team members to recognize problem areas in time to take appropriate remedial measures such as redesigning members, adjusting reinforcing steel details (Fig. 2.7.2), or modifying the concrete specification to reduce the maximum size aggregate or allow self-consolidating mixtures. It also will provide time to use mockups to develop procedures and alert the contractor to critical conditions (refer to **ACI PRC-309-05, "Guide for Consolidation of Concrete"**).

Fig. 2.7.2: Early communication between the contractor and designer resulted in the development of preplanned openings in the reinforcing mat for insertion of the concrete pump hose. (Image courtesy of Ceco Concrete Construction.)

An article from the December 2022 issue of *Concrete International*, **"Reinforcement Congestion in Cast-in-Place Concrete,"** states, "When bidding on congested areas, reinforcement sub-contractors indicate they reduce the overall productivity rate by 20 to 30%. 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." Productivity loss from congested reinforcement is greater than the time and labor of the reinforcement installer when special mixtures and placing methods are required to avoid a lack of consolidation and subsequent post-placement repair. Figure 2.7.3 provides an example of shear wall reinforcement detailed for constructability. The bars are evenly spaced, and headed reinforcing bars were used to minimize congestion.

Fig. 2.7.3: An example of a shear wall reinforcing cage that has been detailed for constructability. (Image courtesy of Headed Reinforcement Corp.).

Consider the following reinforcement constructability logic:

(a) Early in the design process, determine the required reinforcement cover for the structural elements based on the fire resistance rating and environmental exposure conditions. Consider drip grooves at perimeter slabs and beams, as drips will reduce the cover (Fig. 2.7.4).

(b) When designing slabs-on-ground covering large areas, be aware that the contractor's preferred productivity tools will include a laser screed (Fig. 2.7.5). If conventional reinforcing is required, a single mat of reinforcing bars or welded-wire reinforcement (WWR) will be best for constructability. However, a better solution is to reinforce the slab with steel fibers.

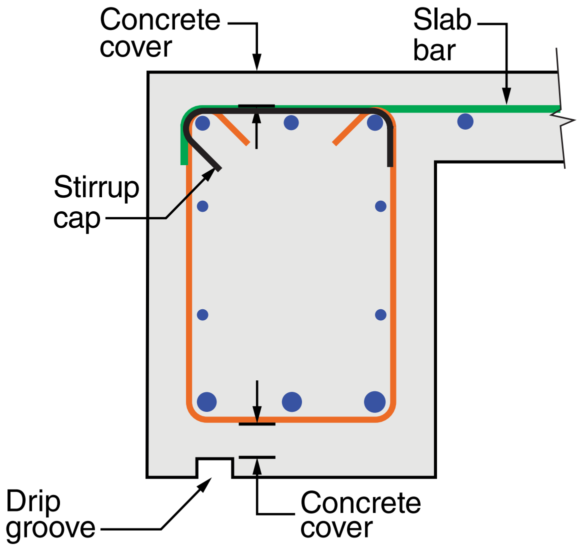


Fig. 2.7.4: Designers should be aware that drip grooves control the cover on exterior framing elements.

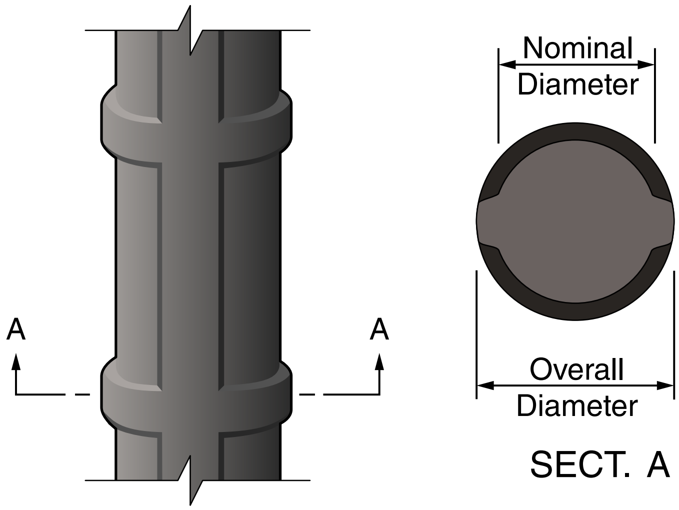
Fig. 2.7.5: A laser screed allows contractors to precisely strike off the concrete during slab-on-ground construction. (Image courtesy of Somero.)

(c) On multi-floor projects (Fig. 2.7.6), the floor construction cycle is a function of the sequencing of the formwork erection, reinforcement placement, concrete placement, and cable stressing if the floors are post-tensioned. Experience shows that cable stressing adds 1 or 2 days to the floor cycle on projects with relatively small floor sizes (< 10,000 ft^2). On larger floor sizes, this scheduling delta evaporates as the PT process fades off the critical path for the concrete construction work.

Fig. 2.7.6: Concrete placement on a floor structure. The structure will not be post-tensioned and the placement area is relatively small, so the contractor has elected to place concrete over the full floor area in a single pour. (Image courtesy of Ceco Concrete Construction.)

(d) Designers are encouraged to provide specific reinforcing details and cut sections for non-typical locations where congestion is a concern, including narrow beams, beam-column joints, or columns with more than 2% longitudinal reinforcement. This step will naturally reveal reinforcing bar constructability concerns, particularly in joints and at splice locations. To best visualize potential congestion, the details should illustrate the reinforcing using actual bar sizes, hook dimensions, and lap splices. The cross sections and profiles of bars must be based on the approximate outside diameter of reinforcing bars, including deformations (Fig. 2.7.7), and bend diameters for stirrups, ties, and hooks should comply with those specified in ACI 315 and ACI 318 to accurately portray bar locations with members (Fig. 2.7.8).

(e) Use standard ACI reinforcing bar bend types that are provided in Chapter 25 of ACI 318, but using the bend diameters indicated in Table 7.2 in the 30th edition of the **CRSI Manual of Standard Practice**. Varying from these standards will reduce productivity, as bar bending is a routine process (Fig. 2.7.9).



Bar size	Approximate diameter outside deformations, in.
#3	7/16
#4	9/16
#5	11/16
#6	7/8
#7	1
#8	1 1/8
#9	1 1/4
#10	1 7/16
#11	1 5/8
#14	1 7/8
#18	2 1/2

Fig. 2.7.7: Approximate diameter outside of deformations of reinforcing bars. (Image courtesy of CRSI.)

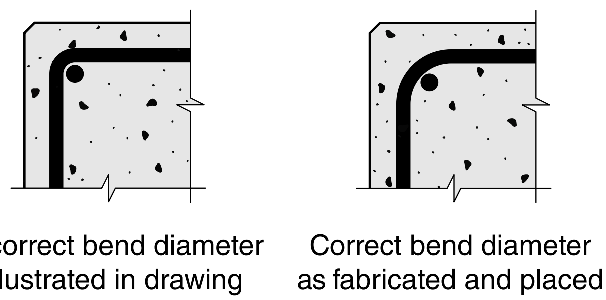


Fig. 2.7.8: Details should be drawn using the correct bend diameter and realistic bar positions. Designers should note that Table 7.2 in the 30th edition of the CRSI Manual of Standard Practice states that standard finished bend diameters for stirrups and ties are 2, 2.5, and 3.25 in. for No. 3, 4, and 5 bars, respectively. These are larger bend diameters than are provided in Chapter 25 of ACI 318 and therefore may slightly reduce the available space for longitudinal reinforcement.

Fig. 2.7.9: A worker uses a bar bender to fabricate standard 90-degree hooks on two No. 9 bars. (Image courtesy of CRSI.)

(f) The material cost premium for Grades 80 and 100 rebars (high-strength reinforcing bars, or HSRBs) can range from 3 to 15% over Grade 60 bars, with Grade 100 at the top of the range. Rolling mill lead times can be longer for HSRBs, suggesting the need for early purchase commitment to the rebar fabricator when HSRBs are used for early project elements, such as foundations. HSRBs allow placement of fewer bars, reducing rebar placement labor, reducing congestion, and improving concrete placement. A small reduction in production rates for placement (weight placed per hour of labor) may be realized if bar size is reduced rather than bar quantity is reduced while maintaining bar size. However, HSRBs provide significant constructability advantages, especially for mat foundations and vertical elements (Fig. 2.7.10).

Designers should therefore design and specify reinforcement based on the highest strength allowed for specific applications by ACI 318 Section 20.2.2.4 and while accommodating the following caveats:

- Some fabricators are not equipped to work with all bar grades. Designers should determine if local fabricators can shear and bend Grade 100 bars.
- While HSRBs can reduce quantities and resolve congestion issues for some elements, thus improving constructability and schedules, designers must also account for the effects of longer development lengths.
- To minimize the potential for errors during fabrication and placement, construction documents should call for no more than two grades of deformed bars, and each bar size should be limited to one grade per element (for example, all No. 4 bars in columns should be Grade 80).

Fig. 2.7.10: Column cage mockups designed and fabricated using different grades of bars. The cage comprising HSRBs (foreground) required significantly less labor for bar placement and will allow much better flow of concrete between bars than would be required in a cage comprising Grade 60 bars (background). (Image courtesy of CKC.)

(g) Use repetitive bar sizes and lengths. Figure 2.7.11 illustrates how to reinforce a sloping wall while using only three bar lengths (A, B, and C). This recommendation also applies to other areas requiring bar splices, including slabs and decks. Further, maximize reinforcing bar sizes while satisfying crack control requirements specified in the Code.

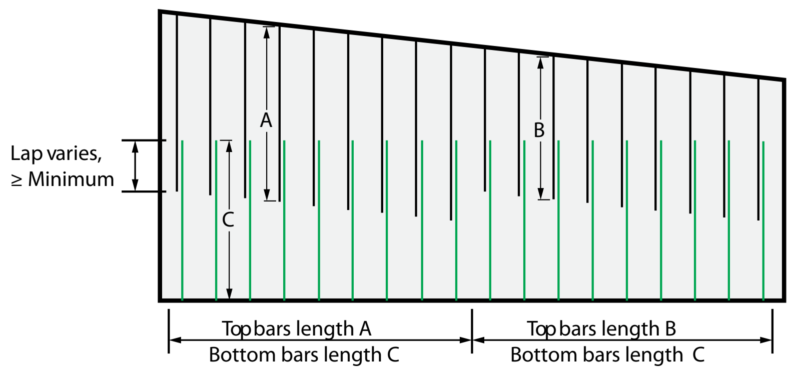


Fig. 2.7.11: The number of unique bars required for a project can be reduced by allowing lap lengths to vary. (Detail from "Design Guide for Economical Reinforced Concrete Structures.")

(h) Use straight reinforcing bars whenever possible, in repetitive bar sizes and lengths, up to the standard length of 60 ft.

(i) Minimize hooks and bends in reinforcing bars if strength development is sufficient in a straight bar. This is especially true for large and long bars. When using larger bars with hooks, ensure the reinforcing bar hook fits within the slab or member depth while considering cover requirements. This constructability challenge becomes more difficult if the slab edge contains cladding embeds that reduce the slab thickness available for reinforcing bars. If a 90-degree hook does not fit, for example, designers should consider using smaller-diameter bars, headed bars, or bars with 180-degree hooks. In all cases, designers should avoid requiring long bars with hooks at both ends (Fig. 2.7.12).

(j) Use stud rails and/or shear reinforcement in lieu of slab drop panels (Fig. 2.7.13).

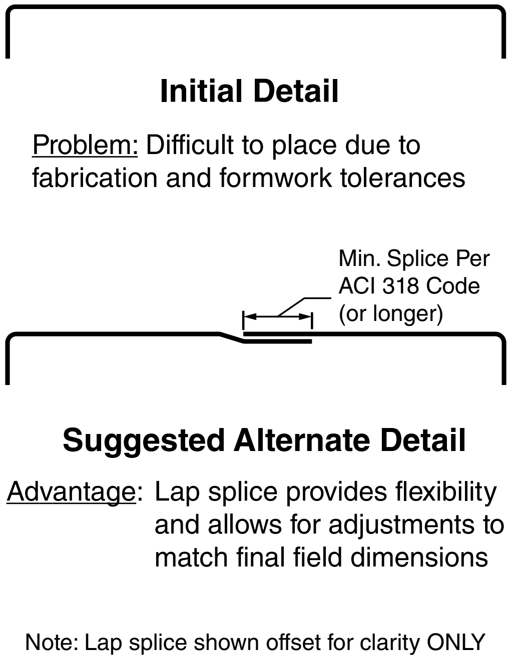


Fig. 2.7.12: Bars with double hooks create constructability issues. Lap splicing of bars allows for field adjustments and ensuring hooks have adequate cover. (Image courtesy of CRSI.)

Fig. 2.7.13: Double-headed stud shear reinforcement (stud rails) can allow slabs to be constructed without drop panels. (Image courtesy of CRSI.)

(k) At slab-column intersections, a portion of the moment is transferred by flexure. For an interior column supporting a slab without drop panels, the Code requires this portion of the moment to be concentrated within three times the slab thickness plus the column width. Figure 2.7.14 is an example of a detail the designer should provide to address reinforcing bar placement within this zone. Design details should also address reinforcing bars required around slab openings.

(l) During concrete placement, walking on slab reinforcement can be a bit treacherous for the placing crew. A constructable solution is to establish a mat of top reinforcing with a regular bar spacing in each direction. Designs incorporating a top mat of No. 4 bars at 12 in. on center in both directions will

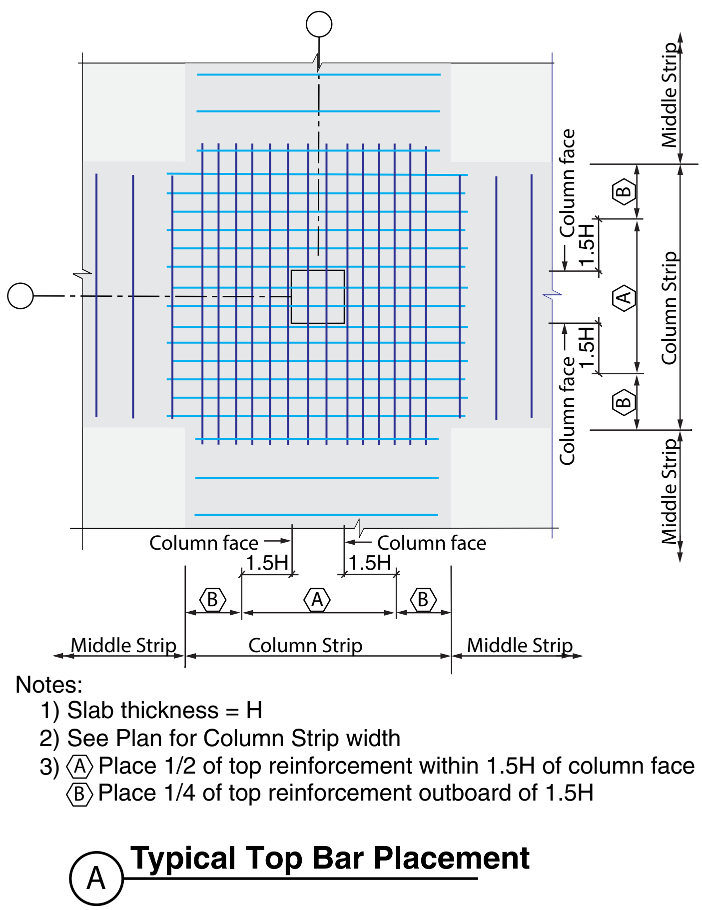
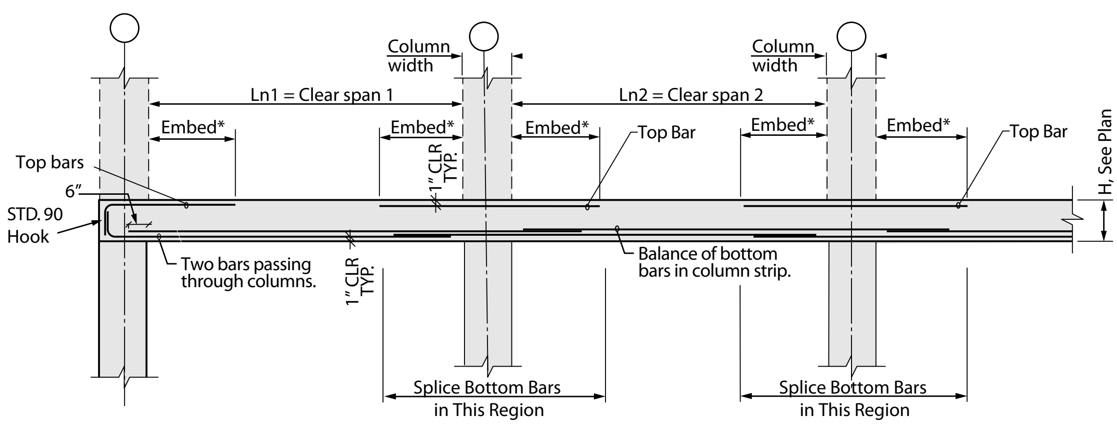


Fig. 2.7.14: An example of a detail that should be provided by the designer to address reinforcing bar placement at slab-column connections.

provide a stiff and predictable grid to protect other reinforcement from displacement and provide a safer base for the workers (Fig. 2.7.15).

Fig. 2.7.15: Crews must walk on the reinforcing in thick slabs and foundation mats during concrete placements. Safe footing can be provided using: (a) grid of closely spaced reinforcing bars; or (b) welded-wire reinforcing placed on top of larger, more widely spaced bars. (Images courtesy of Ceco Concrete Construction.)

(m) Designers should provide a reinforcement layering detail to identify which reinforcing bars are to be placed in the outer and inner layers of slab and mats. Figure 2.7.16 includes a note to clarify and ensure reinforcing bar placement is consistent with the design intent. To maximize structural efficiency, reinforcing bars in the direction of the larger bending



Typical Column Strip

Notes:
1. Ln* = greater of adjacent clear spans
2. Embed* = Maximum of 0.3Ln* or 5(H-1)
3. See Typical DTL A for Top Bar Placement
4. Provide Class B tension lap splices for all bottom bars
5. Headed shear reinforcement not shown for clarity

TYPICAL REINFORCEMENT PLACING SEQUENCE
1. Place all E-W slab bottom bars (mat bars plus additional)
2. Place all N-S slab bottom bars (mat bars plus additional)
3. Place all E-W PT strands
4. Place all N-S PT strands
5. Place all N-S slab top bars
6. Place all E-W slab top bars

Fig. 2.7.16: An example layering detail for bars in an elevated deck. The note within the red rectangle helps to ensure that bar placements are consistent with the design intent. PT strands are not shown for clarity.

moments should be placed in the outer layers. Further, consistent bar diameters should be maintained, as a slab with various bar sizes will require multiple bar supports and will be difficult for the placing team to manage without error or delay.

Foundation mats comprising heavy reinforcing bars may require in-place assembly. In many markets, bar placers will commonly relocate (drop) a portion of the structural bars to serve as support bars for the bottom layer of a reinforcing bar mat (Fig. 2.7.17). The support bars will be secured on bar supports at the spacing required to support the bottom layer of the mat, the bottom layer will be placed and tied at the required spacing, and the second layer of the mat will be placed and tied. To ensure communication regarding cover requirements, designers should consider allowing this practice using details or notes. For further information, refer to **CRSI Placing Reinforcing Bars, 10th Edition** and **CRSI ETN-C-3-14, Dropping Main Reinforcement Bars for Use as Support Bars**.

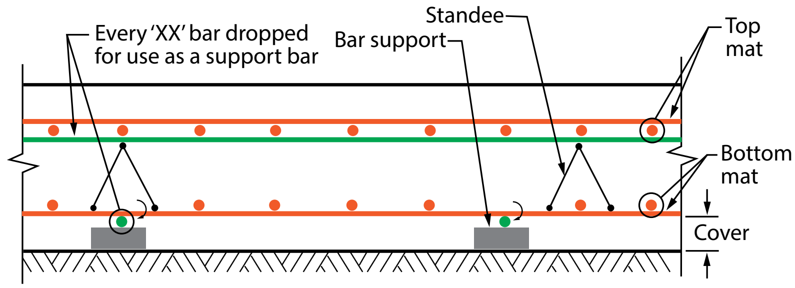


Fig. 2.7.17: Schematic section for a foundation with two mats of reinforcing bars. Support bars are used to ensure each layer of bars can be secured at the specified spacing and depth. In many markets, support bars are sourced by relocating (dropping) structural bars from the second layer in a bottom mat or from the top layer of the top mat (these are commonly termed "buried contract bars"). In doing so, the rebar supplier and placer will improve productivity by not supplying and placing additional bars strictly for support. Provide a typical detail in the drawings offering this option if the approach is acceptable to the designer. (Note that the relocated bars in the bottom mat of bars will encroach on the specified cover as shown.) (Image courtesy of CRSI.)

(n) On projects that have an irregular column layout, constructability and inspection will be enhanced by designing top and bottom reinforcing as evenly spaced, orthogonal bar mats (Fig. 2.7.18). If additional reinforcing is required, the standard mats can be supplemented with skewed bottom bars and top bars (placed parallel to the orthogonal grids and centered on the column). For more information, refer to *Concrete International*, November 2012, "**Detailing Corner: Reinforcing Bar Layout for Two-Way Slabs**."

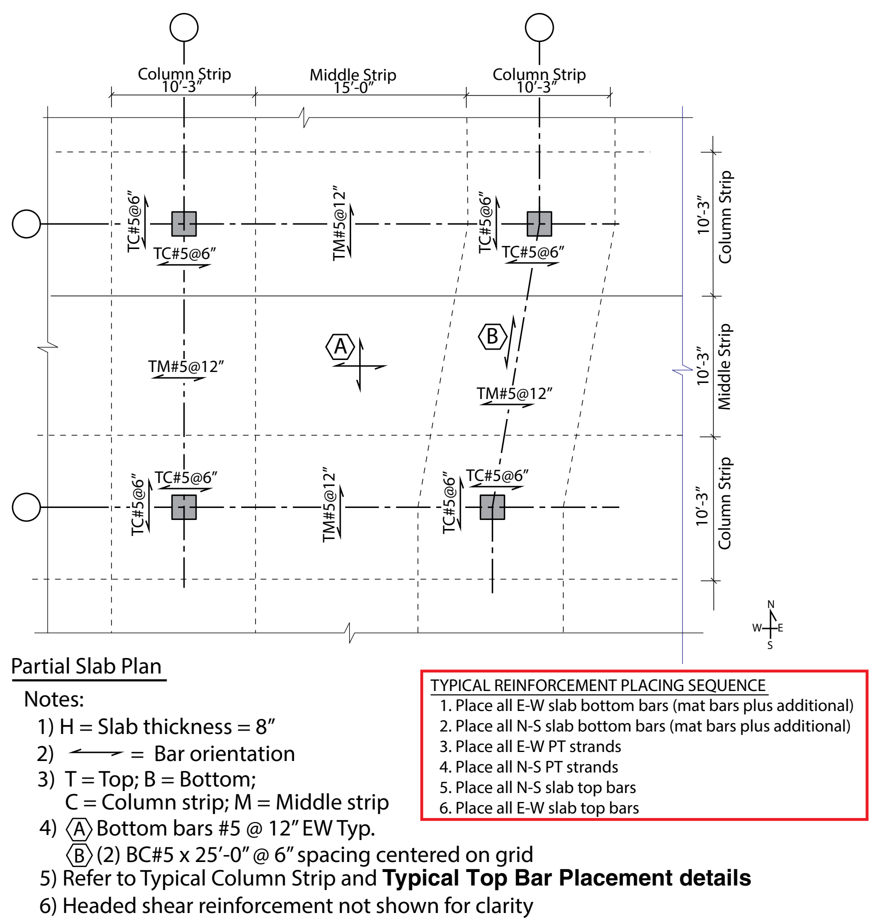


Fig. 2.7.18: To improve constructability of a project with an irregular column layout, two orthogonal grids of regularly spaced top and bottom reinforcement can be supplemented with additional top and bottom bars.

(o) For constructability, clearly indicate that slab-top reinforcing bars pass over beam reinforcing along column lines. Slab bars are typically placed above the top bars in the beam because the minimum cover specified for the slab bars is smaller than that specified for the beam bars (Fig. 2.7.19 and 2.7.20).

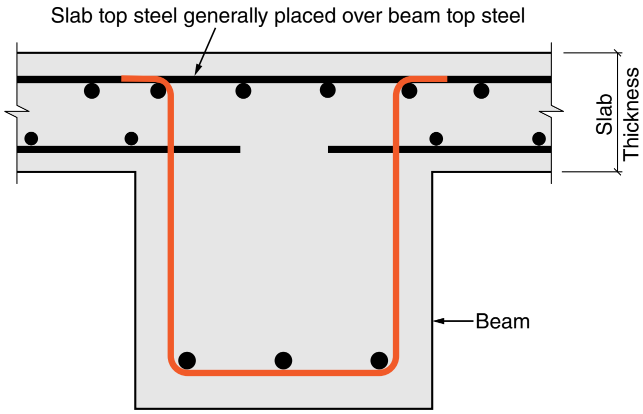


Fig. 2.7.19: When slabs are supported on beams, construction documents should include a detail showing the placement of slab top reinforcing passing over a beam.

Fig. 2.7.20: Reinforcing bars at a beam-slab-column connection (photo courtesy of Ceco Concrete Construction.) Note that ACI 318 Section 24.3.4 requires tension reinforcement in beam and girder flanges (top bars at column intersections) to be distributed within the lesser of the effective flange width bf or a width equal to 10% of the clear span ln of the flexural member (refer to Fig. 2.7.27).

(p) If allowed by the ACI 318 Code, designers should detail closed stirrups as two pieces (Fig. 2.7.21(a)), with one piece comprising the bottom and sides of a unit and a second piece comprising a horizontal bar with hooked ends (a top cap). However, construction documents should also include a note allowing one-piece stirrups (Fig. 2.7.21(b)) in pre-assembled cages. Two-piece stirrups allow the top cap to be installed after installation of top and bottom beam bars. The cap can have a 135-degree bend and a 90-degree bend, allowing the cap to be installed with all longitudinal bars in place. Stirrups in beams that do not require closed stirrups should be detailed with out-turned hooks on the vertical legs, opening the beam for bar and concrete placements and vibrator use (Fig. 2.7.21(c) and 2.7.22).

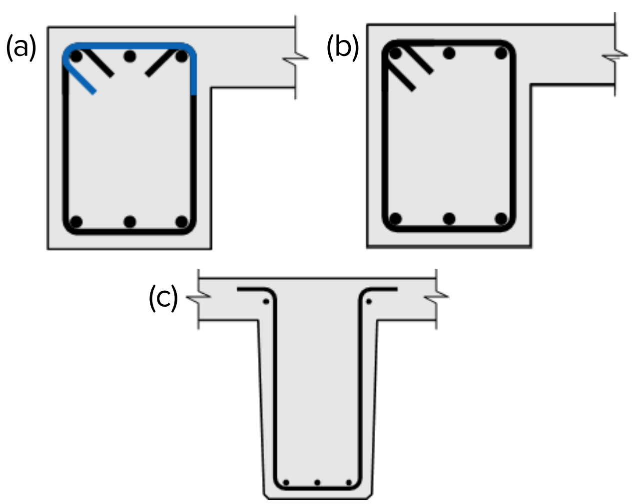


Fig. 2.7.21: Stirrup cage options: (a) two-piece stirrup; (b) one-piece stirrup, and (c) stirrup with out-turned hooks. (Image courtesy of CRSI.)

Fig. 2.7.22: Beam stirrups having out-turned hooks and open tops enable concrete placement and consolidation. Other constructable solutions include stirrups comprising baskets fabricated using welded-wire reinforcement. (Image courtesy of Ceco Concrete Construction.)

(q) ACI 318 addresses the maximum spacing between the stirrup legs in wide beams. Figure 2.7.23 provides potential stirrup configurations. Figure 2.7.23(a) shows a beam with three separate closed stirrups across the beam width. This detail is difficult to construct because laborious measurements are required to control the covers on the beam sides and the closed stirrups make it difficult to install longitudinal bars (even preassembly would be difficult). Figures 2.7.23(b) and (c) provide constructability improvements. The perimeters of both cages are defined by a single stirrup with an open top and a cap tie, so cover is readily controlled. Further, both cages allow installation of longitudinal bars prior to installation of the top caps (Fig. 2.7.24).

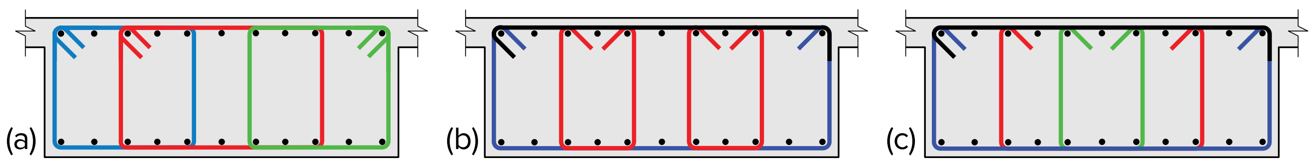


Fig. 2.7.23: Potential multi-leg stirrup configurations for a wide beam: (a) multiple closed stirrups across the width of a beam (not constructable); (b) an open-top perimeter stirrup with nested internal open-top stirrups; and (c) an open-top perimeter stirrup with two internal open-top stirrups. Detail (c) is preferred, as Details (a) and (b) will require stacking of three stirrups and can cause congestion.

Fig. 2.7.24: Wide beams with multi-leg stirrups, open to the top. The beam cage can be closed using a separate top cap. (Image courtesy of Conco.)

(r) Intersecting beams should have identical depths, so the designer must specify the primary beam and secondary beam to establish reinforcement layering priorities. Adding clarification, such as showing the additional bottom cover for the secondary beam reinforcing will improve constructability by preventing field conflicts and installation errors (Fig. 2.7.25). (Refer to **ACI 315-18 Guide to Presenting Reinforcing Steel Design Details**.)

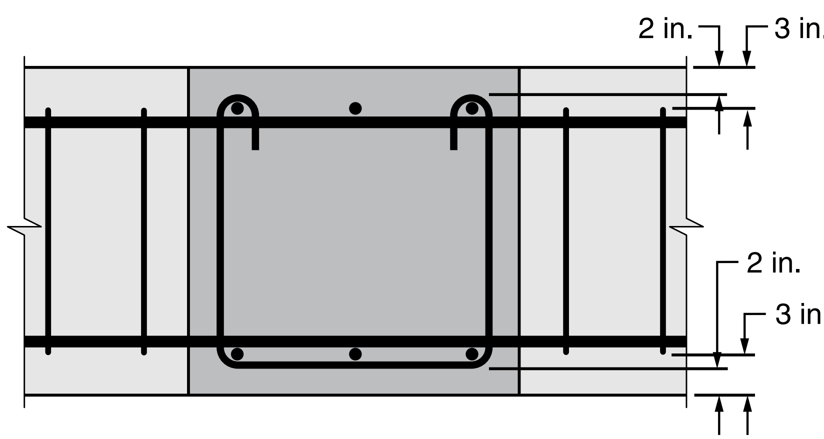


Fig. 2.7.25: The designer must establish the layering of reinforcing at intersecting beams. The addition of required cover values will add clarity to the construction documents.

(s) The width of a beam relative to its supporting columns has a major impact on constructability. First, it affects formwork cost. Referring to Fig. 2.7.26, the formwork in either Case A or Case B is much simpler than the formwork in Case C, where the beam is narrower than the column. The second constructability impact of a wide beam is its potential to relieve congestion at column intersections. Even though the formwork is simple in Case A, where the width of the beam is the same as that of the column, it is good practice to have a wider beam (Case B) to avoid interference between the longitudinal corner bars of the beam and the column corner bars. If beam widths are least 4 in. wider than their supporting columns, for example, the outermost longitudinal bars in the beam can pass outboard of the vertical bars in the column. This simplifies bar placement and increases the spacing between longitudinal bars—concrete placement and consolidation will be enhanced.

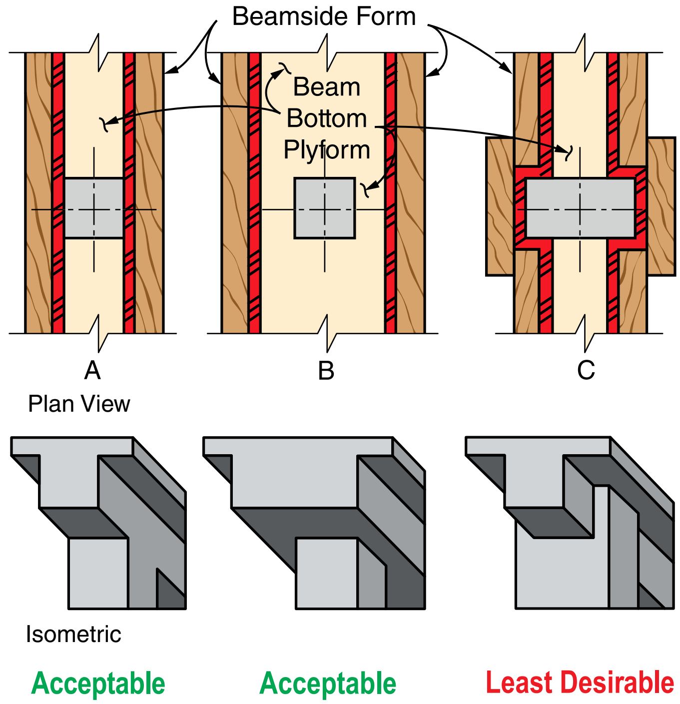


Fig. 2.7.26: The greatest economies in formwork construction are achieved when beams are at least as wide as columns. For parking structures built using steel beam formwork systems (Fig. 2.6.20), Plan View C is most desirable.

Examples of Cases B and C are shown in Fig. 2.7.27(a) and (b), respectively. The example in Fig. 2.7.27(a) has sufficient width to allow four top beam bars to pass outboard of the column bars. However, there may have been even greater opportunities to reduce the congestion of bars passing through the column cage. For example, the ACI 318 code requires all tensile

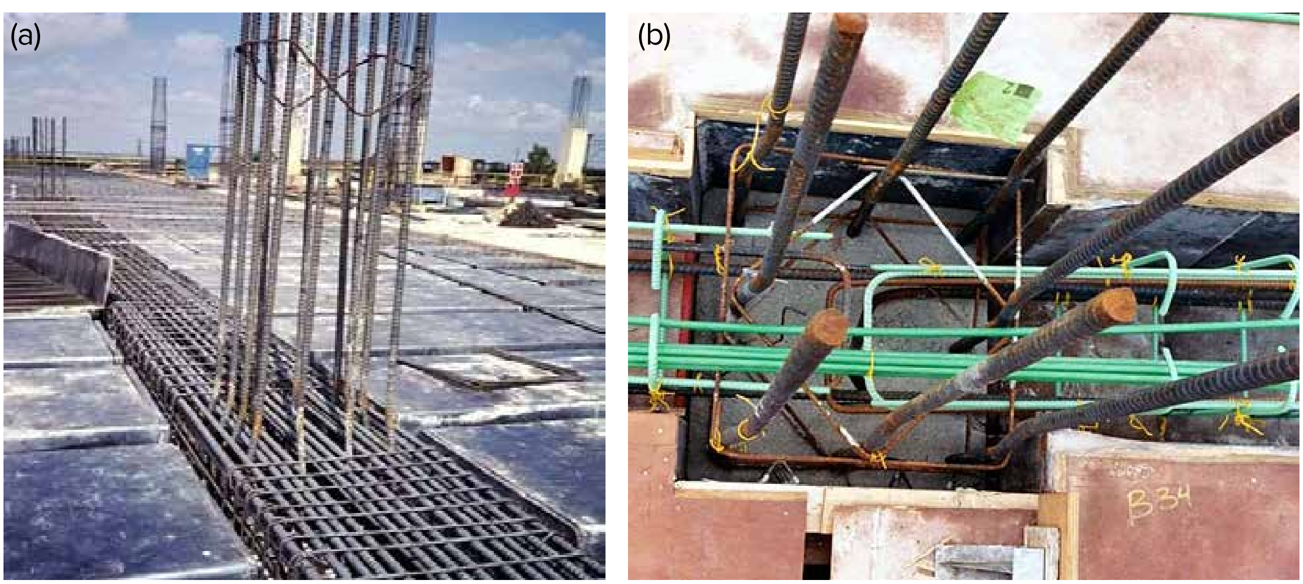


Fig. 2.7.27: Formwork and reinforcement at column-beam intersections: (a) a desirable beam width allows crews to route beam reinforcement around column bars; and (b) an undesirable beam width adds to formwork complexity and can result in interference between beam and column bars. (Images courtesy of CRSI.)

reinforcement required for strength to be located within the lesser of the effective flange width and 10% of the clear span (Section 24.3.4). The shown beam span may be sufficient to invoke this requirement. Further, the shown beam may not require closed stirrups if 25% of the maximum positive moment reinforcement is continuous. Using out-turned stirrups with 90-degree bends will further reduce reinforcing congestion at columns (Fig. 2.7.28).

Designs incorporating wide beams must comply with the design and detailing requirements for beam-column joints, as stated in ACI 318 Chapter 15. Beam-column joints in special moment frames must also comply with the requirements in ACI 318 Section 18.6.2. This section limits the projection of beam widths beyond the width of the supporting column on each side to the lesser of c2 or 0.75c1, where c1 and c2 are column dimensions in the direction of the beam span and transverse to the beam span, respectively (Fig. 2.29). Example 6 in

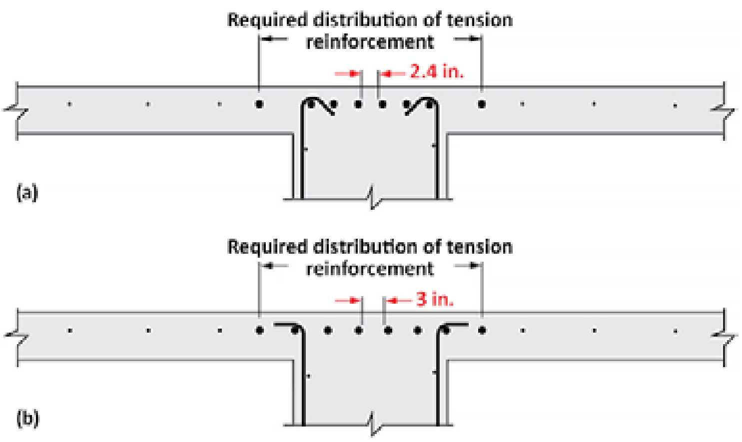


Fig. 2.7.28: ACI 318 Section 24.3.4 requires bonded tension reinforcement to be distributed within the lesser of the effective flange width b_f or a width equal to 10% of the clear span ℓ_n of the flexural member: (a) key features of Fig. E5.12 from the ACI Reinforced Concrete Design Handbook illustrate an example in which two of nine top bars (bar size No. 9) must be placed outboard of the girder web to meet the reinforcement distribution requirement; and (b) a similar detail, showing that constructability can be further enhanced by using out-turned stirrups with 90-degree hooks (the modification allows clear spacing over web to increase from 2.4 to 3 in.).

Recommendations for Design of Beam-Column Connections in Monolithic Reinforced Concrete Structures illustrates how a wide, shallow beam can allow designers to limit congestion at column intersections. Additional examples demonstrating joint-shear calculations are provided in Section 9.9 of **ACI Reinforced Concrete Design Handbook**.

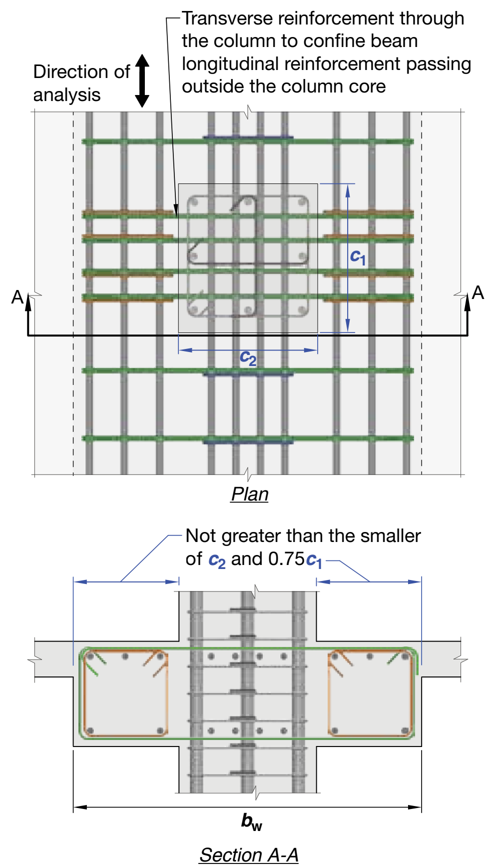


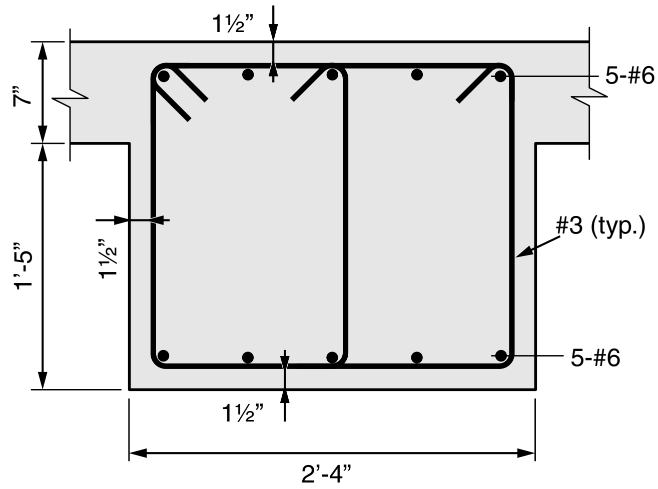
Fig. 2.7.29: Fig. R18.6.2 from ACI 318 illustrates the maximum effective width allowed for beams in special moment frames. This limit can conservatively be extended to beams where reinforcement congestion at beam-column intersections is a concern.

(t) Tolerances on member depth, fabricated bars, and cover should be considered when specifying minimum cover. As shown in Fig. 2.7.30, a combination of these tolerances will allow the provided cover to fall below the acceptable cover. To ensure acceptable cover is maintained, additional cover should be provided in details and the specification. Further information can be found in **Guidelines for Tolerance Compatibility in Steel Reinforced Cast-in-Place Concrete Construction**.

Tolerances on beam width, bars, and cover should also be considered with selecting beam width. In a December 2022 *Concrete International* article "**Reinforcement Congestion in CIP Concrete**," the ASCC Constructability Committee recommends a minimum beam width formula that provides the allowances for construction tolerances or requirements for adequate placement and consolidation of concrete. This formula suggests minimum beam width sizes should be increased to incorporate stirrup fabrication tolerance and bar placement tolerances. "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."

Achieving acceptable cover over beam stirrups can be a challenge in structures with sloping slabs. For constructability, designers must specify where the beam depth is to be measured. Referring to Fig. 2.7.31, note the difference between the beam depth at its center line and the beam depth at its downhill side. If the stirrup is detailed using the beam depth at its center line, the clear cover on the low side will be compromised.

(u) ACI 318 establishes the minimum spacing of reinforcing bars to allow for concrete consolidation. It also defines the maximum spacing of bars for crack control. Based on these requirements, Tables 2.7.1 and 2.7.2 set out the maximum and minimum numbers of reinforcing bars permitted in a single layer for a given beam width.



Beam thickness tolerance: +½ in., - ⅜ in.
Overall height and width of rebar cage tolerance: ±½ in.
Top cover can be reduced by as much as ½ + ⅜ = ⅞ in.
Resulting cover to #3 stirrups = 1½ - ⅞ = ⅝ in.
Concrete cover tolerance: -½ in.
Acceptable cover = 1½ - ½ = 1 in. > Provided cover = ⅝ in.

Fig. 2.7.30: Combined tolerances can result in beams with less than acceptable cover. (Image courtesy of CRSI.)

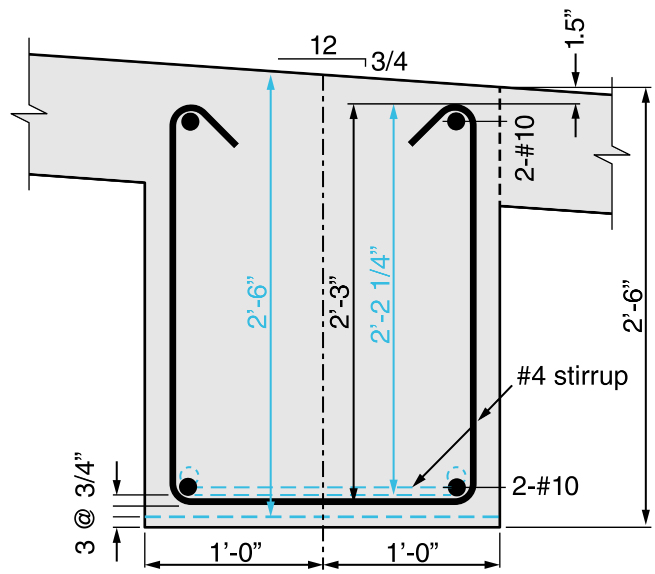


Fig. 2.7.31: In structures with sloping slabs, designers should specify that the beam depth is defined at its downhill side. (Image courtesy of CRSI.)

The table data were derived from ACI 318 minimum and maximum spacing considering the overall bar diameter, clear cover to the stirrup of 1.5 in., nominal maximum aggregate size of 3/4 in., and stirrup sizes as required by the size of the longitudinal bars.

Table 2.7.1: Maximum number of longitudinal reinforcing bars permitted in a single layer. Note that lap splices are not reflected in these quantities (Source: Recommended Details for Reinforced Concrete Construction).

Bar size	Beam width, in.												
	12	14	16	18	20	22	24	26	28	30	36	42	48
No. 4	5	6	7	8	10	11	12	14	15	16	20	24	28
No. 5	4	5	7	8	9	10	11	13	14	15	19	22	26
No. 6	4	5	6	7	8	9	10	11	12	14	17	20	23
No. 7	3	4	5	6	7	8	9	10	11	12	15	18	21
No. 8	3	4	5	6	7	7	8	9	10	11	14	16	19
No. 9	3	4	4	5	6	7	8	8	9	10	12	15	17
No. 10	2	3	4	5	5	6	7	7	8	9	11	13	15
No. 11	2	3	3	4	5	5	6	7	7	8	10	11	13

Overall bar diameter (in lieu of nominal diameter) is used for the longitudinal reinforcement (refer to Fig. 2.7.4)
Cover to stirrups = 1.5 in.
Nominal maximum aggregate size d_{agg} = 3/4 in.
No. 3 stirrups are used for No. 4, 5, and 6 longitudinal bars, and No. 4 stirrups are used for No. 7 and larger longitudinal bars.

Table 2.7.2: Minimum number of longitudinal reinforcing bars required in a single layer (Source: Recommended Details for Reinforced Concrete Construction).

Beam width, in.												
12	14	16	18	20	22	24	26	28	30	36	42	48
2	2	3	3	3	3	3	4	4	4	5	5	6

Grade 60 reinforcement with f_s = 40,000 psi.
Overall bar diameter is used for the longitudinal reinforcement (refer to Fig. 2.7.4).
Least distance from the surface of the flexural reinforcement to the tension face of the section = 2.0 in.

(v) When beams have multiple parallel layers of hooked bars at a beam-column connection, congestion may make it difficult to provide sufficient development length of the inside bar. A constructable solution is to use headed bar, as shown in Fig. 2.7.32. Headed bars offer several constructability advantages. They mitigate congestion; eliminate concerns with possible insufficient embedment; reduce the amount of coordination needed between the reinforcing bar fabricator, concrete contractor, and reinforcing bar placing contractor; and improve jobsite productivity by their ease of placement.

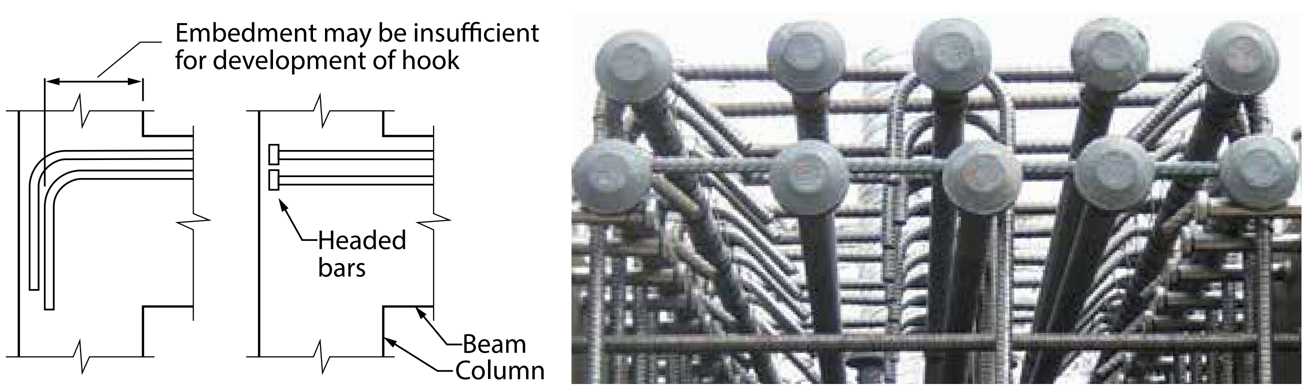


Fig. 2.7.32: Headed reinforcement can help avoid congestion and ensure adequate embedment to develop bars. (Detail source: STRUCTURE Magazine, *May 2011, "Tips for Designing Constructible Concrete Structures, Part 2." Image courtesy of Headed Reinforcement Corp.)*

(w) Continuous bottom reinforcing bars in beams are typically lap spliced over or near columns. The details in Fig. 2.7.33 provide potential splice options. In Detail 1, all bottom bars are spliced over the columns. This can cause significant congestion, especially when the beam is not wider than the column and/or when a large amount of continuous reinforcement is required. In Detail 2, the bottom bars are spliced on either side of the column. This reduces the congestion over the column. However, detailing and preassembly of the cages are slightly more complex operations, so installation times will be high. Further, multiple-bay cages are very difficult to install. In Detail 3, the bottom bars are spliced on the same side of each column. This solution is more productive to install, although the cages must be oriented correctly as installation progresses across the structure. In Detail 4, the bottom bars stop short of the columns faces. To provide continuous bars, splice bars are placed inside the column and extend outside the column a full lap length on each end. While this solution will require added steel for the second splice at each column, it is the most constructable solution. Not only does it reduce beam-column congestion, it allows rapid placement of preassembled cages and is a good solution for multiple-bay beams. Furthermore, this option provides a ready means for locating splices outside a distance of twice the beam depth from the column face, as is required in special moment frames in Seismic Design Category D, E, and F (refer to ACI 318 Section 18.6.3.3).

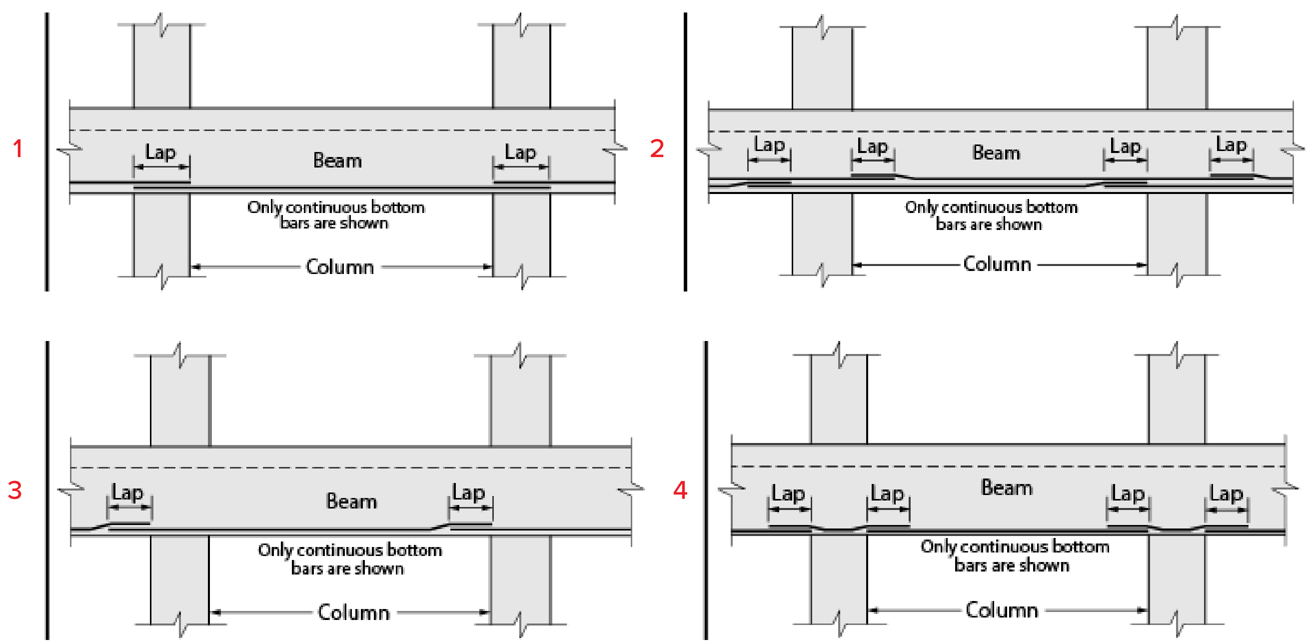


Fig. 2.7.33: Potential options for lap splices of continuous bottom reinforcing bars in beams. (Image courtesy of Concrete International*, December 2009, Beam-Column Joints, and CRSI Reinforcing Bars: Anchorages and Splices, 2022.)*

(x) Configuring reinforcing steel to provide access for pump hoses and vibrators is critical for proper concrete placement. In a heavily reinforced member, make allowances for gaps between bars that will allow a vibrator to reach the bottom of the member. Gaps should be 6 x 6 in. in plan, continuous over the full member depth, and spaced 8 to 10 ft apart. A December 2022 article in *Concrete International*, "**Reinforcement Congestion in CIP Concrete**," provides greater detail (Fig. 2.7.34).

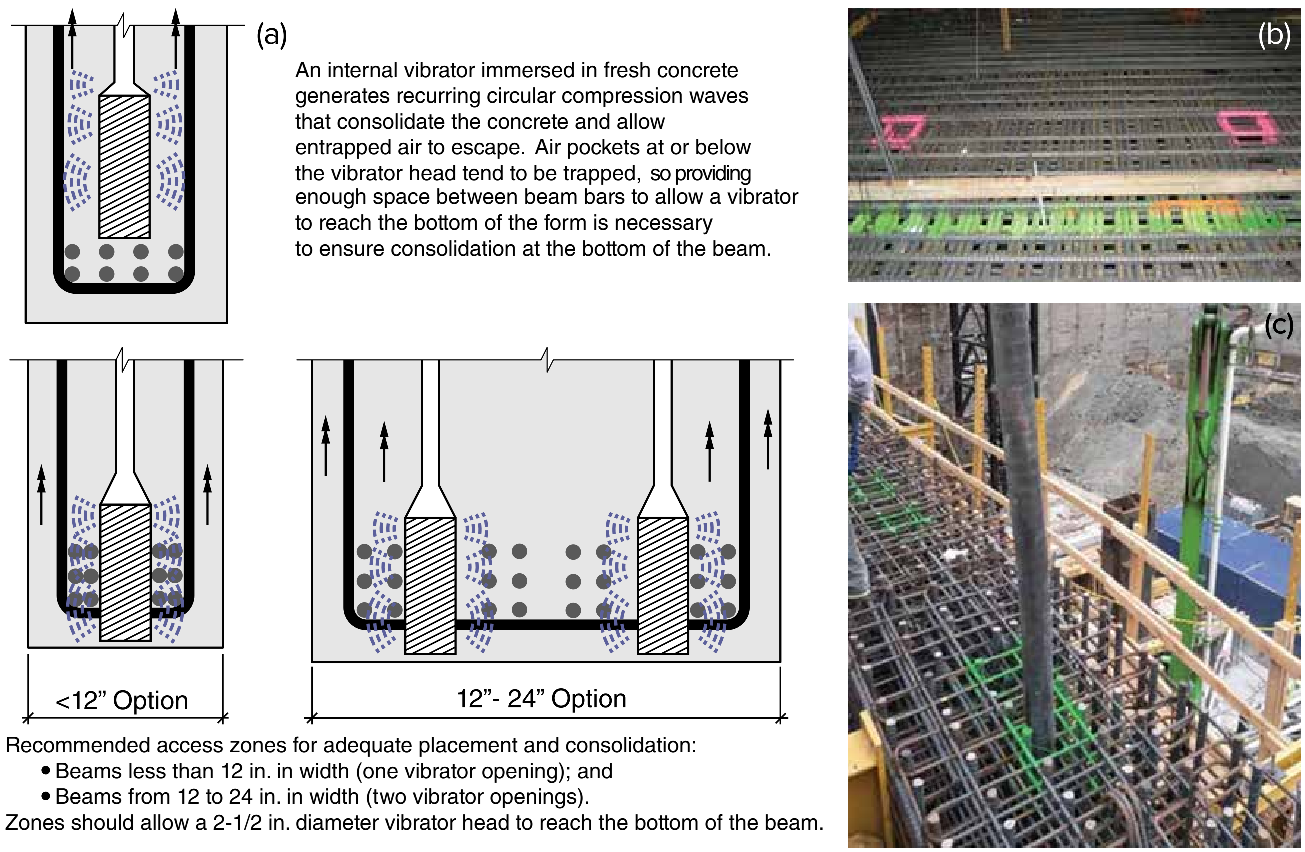


Fig. 2.7.34: Images from “Reinforcement Congestion in CIP Concrete” illustrate the need for pump hose and vibrator access zones: (a) schematics demonstrate the reasons for access; (b) access zones in a mat are marked in pink paint; and (c) access zones marked in green paint (spaced 10 ft apart over the top of a congested shear wall).

(y) Construction joints are necessary and contribute to improving construction productivity by allowing formwork reuse and efficient placement sequencing and extents. The use of dowel bar couplers at construction joints should be embraced (Fig. 2.7.35). These mechanical reinforcing splice systems are also known as form savers because they protect formwork sheathing from damage, thereby maximizing reuses and minimizing the need for formwork repairs. Couplers also expedite form placement and removal, saving labor and minimizing the risk of damage to embedded bars and the surrounding concrete.

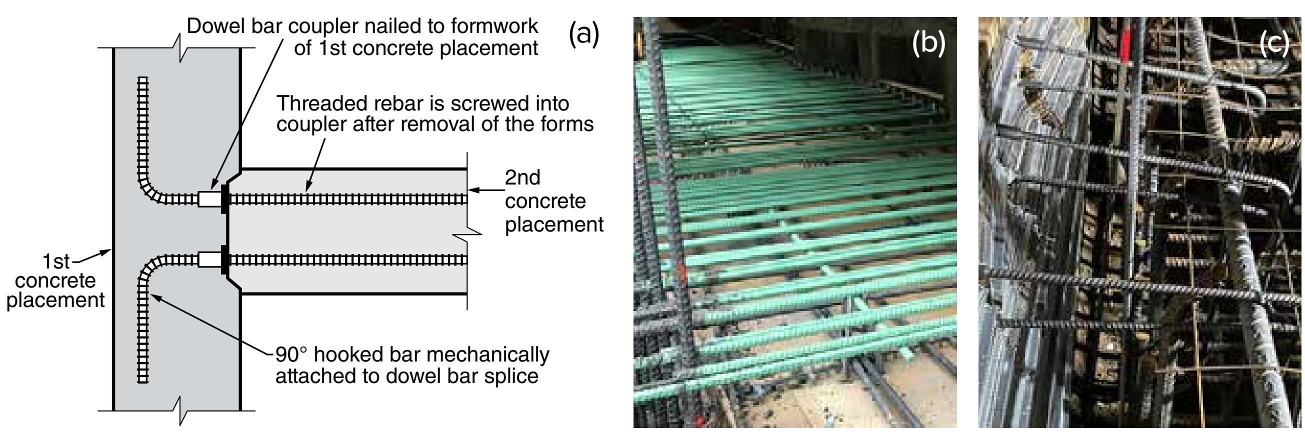


Fig. 2.7.35: Examples of dowel bar couplers at construction joints: (a) a suggested detail from “Design Guide for Economical Reinforced Concrete Structures”; (b) couplers attached to slab formwork (image courtesy of McHugh); and (c) couplers in a foundation construction joint incorporating a stay-in-place form (image courtesy of Hensel Phelps). Note that threaded dowel bars must not be bent prior to installation in a coupler.

(z) PT strands are tensioned at their live end anchors using stressing jacks (Fig. 2.7.36). Contractors will strive to minimize construction joints, primarily to limit the waiting time to stress tendons between adjacent pours. However, friction losses in strands increase with distance from the jack, so joints may be unavoidable. Many contractors will terminate strands at approximately 130 ft from the live-end anchors if strands can be tensioned at only one end (single pull), and they will terminate strands at approximately 160 ft if strands can be tensioned at both ends (double pull). These distances can be increased by adding extra tendons, so designers should consult with PT system suppliers to determine the preferred limits for construction joint spacing.

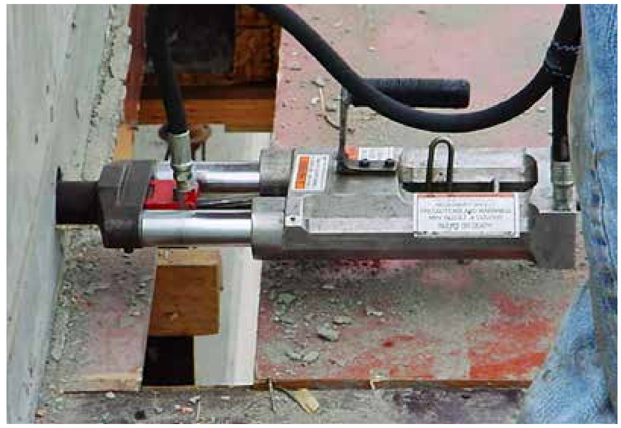


Fig. 2.7.36: The jacks used for tensioning PT cables require a 3 ft wide accessible zone. (Image courtesy of Post-Tensioning Institute.)

The designer should specify permissible locations for PT construction joints. When considering joint locations, be aware of the need for access to the joint for PT stressing. Considerations will include direction and location of cable tensioning, size of the pour strip bay, and temporary structural properties of that bay. If possible, select a construction joint location that avoids crossing beams or walls, as both create construction complexities that hamper productivity.

Ideally, the joint will be opposite an open side of the structure, allowing the strands to be tensioned without the need to delay the adjoining placement to allow for concrete hardening and strand tensioning. Furthermore, because tensioning away from the construction joint avoids elongation of the cables at the construction joint, the cables can immediately be draped as required by the construction documents, with no need for re-draping.

On projects (for example, parking structures) that require a delay strip to provide time for slab shortening, locate the pour strip midspan and design the bay to comprise of self-supporting cantilevered slabs (without the need for costly backshoring) after cables are tensioned. A **STRUCTURE Magazine article** from December 2021 provides more detail. In addition, consider the use of a mechanical reinforcement splice system that eliminates the traditional pour strip and maintains reinforcing bar continuity while allowing for shrinkage (Fig. 2.7.37). While such devices do not minimize the time for tensioning or re-draping, they can expedite the schedule by eliminating the need for placement of a pour strip and the associated shoring conflicts for following trades.

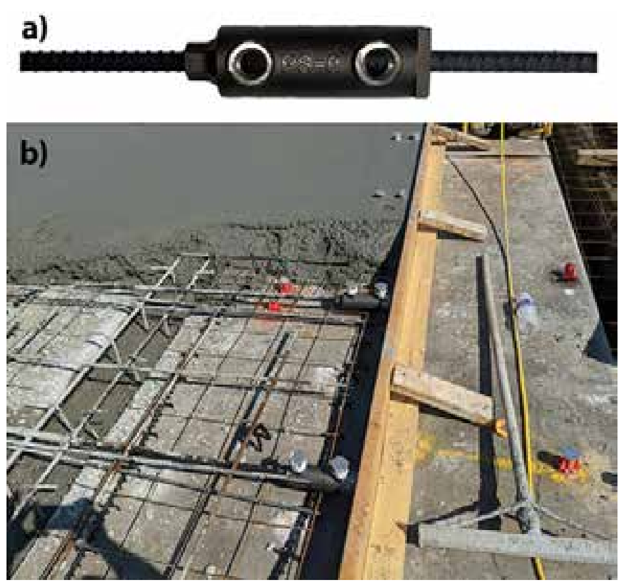


Figure 2.7.37: A reinforcement splice system capable of carrying shear across a joint without restraining shrinkage of adjacent bays: a) a coupler with bars; and (b) devices installed in the first pour side of a construction joint.

(aa) When designing slab reinforcement, consider reinforcing bar conflicts with adjacent embedded items (for example, electrical conduit and junctions; mechanical, electrical, and plumbing (MEP) items and tubing; cladding attachment anchors; headed studs; and anchor bolts). Look for limited spacing between embedded items, as such conflicts can impede concrete flow and consolidation. A September 2018 *Concrete International* article, **Constructability of Embedded Steel Plates in Cast-in-Place Concrete**, provides greater detail. Figure 2.7.38 shows one of several details contained in the article.

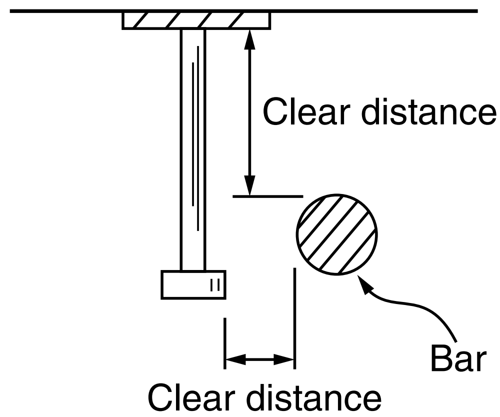


Fig. 2.7.38: Concrete flow can be impeded if the clearance between embedded items and the nearest reinforcing bar is too small. ACI 117-10 requires that the distance is at least the bar diameter, the largest aggregate size, or 1 in. (25 mm).

Non-structural embedded items (typically, MEP systems) are inclusions that can conflict with reinforcing bars and post-tensioning cables (Fig. 2.7.39), so designers should anticipate the need for additional reinforcing or structural depth. On many projects, non-structural embeds arrive at the jobsite after the reinforcing drawings are complete and have been approved (or worse—after the bars and cables have been fabricated and are on site). If the non-structural embeds have not been accounted for in the structural details and/or are late on site, unanticipated conflicts will occur, leading to inaccurate placements and rework. Productivity will suffer. Figure 2.7.40 illustrates common conflicts and a tool that can be used by design teams to find (and avoid) conflicts.

Fig 2.7.39 Electrical conduit should not impede PT strand profiles, (Image courtesy of Amsysco.)

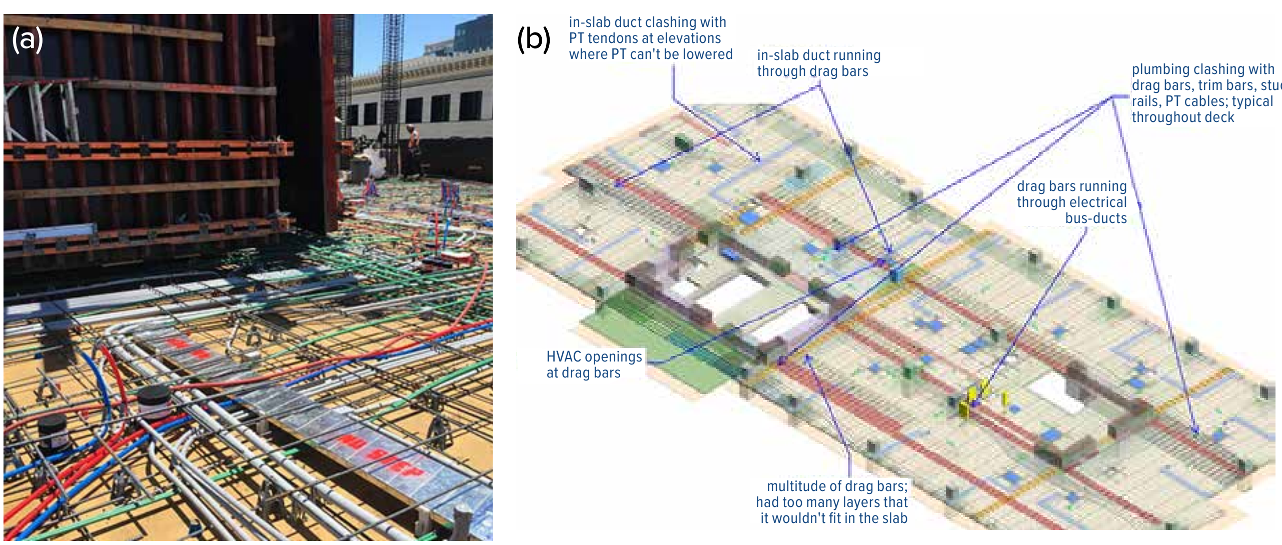


Fig. 2.7.40: Non-structural embeds can conflict with reinforcing bars and strands: (a) sleeves, conduit, and ducts can create major conflicts within elevated slabs; and (b) a 3-D model with all embedded structural and non-structural systems in a floor structure can help the design team avoid conflicts that will ultimately add cost to the project owner. (Images courtesy of CKC.)

Designers should not, however, wait for MEP coordination to approve PT or reinforcing bar fabrication and placement drawings. Tendon quantities, profiles, and calculations are related to the structural design and have nothing to do with MEP embeds. Whereas sweeping tendons around minor openings and embeds should be factored into the PT placement drawings, many suppliers will account for sweeps by fabricating tendons with additional length to account for sweeping tendons around minor openings.

MEP design often occurs late in the design process, so structural designers should pre-plan to minimize potential jobsite disruptions. Steps can include specifying sleeves in beams on regular intervals, in anticipation of the needs of the MEP designer. When their design process is initiated, they will have location options for their system installations. Identify areas of potential MEP equipment installation, such as the roof level. Concentrations of equipment may require large amounts of conduit and/or piping, so design teams must work together to develop details and routing options that can avoid conflicts that will affect structural integrity and concrete placement (Fig. 2.7.41). Rather than wait for the exact location and weights of equipment, design a larger area for the anticipated extra structural capacity to provide flexibility for the MEP designer. And don't wait for the construction document phase to locate sprinkler and water line penetrations through slabs, walls, and beams. These can be located and sized during the design development phase.

Fig. 2.7.41: This heavy concentration of electrical conduit conflicts with vertical reinforcement and will make it almost impossible for concrete to flow between the conduit and the forms below. (Image courtesy of Ceco Concrete Construction..)

Vertical and lateral slab edge movements will affect cladding and curtainwall systems. Structural designers should communicate early with cladding system designers, as early coordination could allow the structual team to make design modifications that will minimize structural movements sufficiently to allow the use of standard embeds rather than unique connections requiring long lead times (Fig. 2.7.42). Of course, even

Fig. 2.7.42: Cladding connection systems are not all typical and should be considered for constructability in the reinforcing design as they may reduce clearance or displace reinforcement. (Image courtesy of CKC.)

standard embeds (Fig. 2.7.43) may require that continuous reinforcing is detailed to pass below the embeds to avoid conflicts.

Fig. 2.7.43: Structural designers must coordinate embedded plates, anchors, reinforcing bars and PT systems. (Image courtesy of Ceco Concrete Construction.)

(bb) The **Post Tensioning Institute** (**PTI**) document, PTI DC20.9-11, "Guide for Design of Post-Tensioned Buildings," provides extensive details and descriptions of construction procedures. It is therefore a great resource for designers of PT floor systems, one-way and two-way slabs, vertical elements, and lateral force-resisting systems. Key constructability tips are also included in a new code and commentary for post-tensioned structures, which is nearing release and will be used in conjunction with ACI 318.

(cc) One-way PT slabs often require temperature strands that are perpendicular to the span strands (uniform tendons). The temperature strands do not require specific support chairs. Instead, the most constructable solution is to support the temperature strands upon the uniform strands, as shown in Fig. 2.7.44.

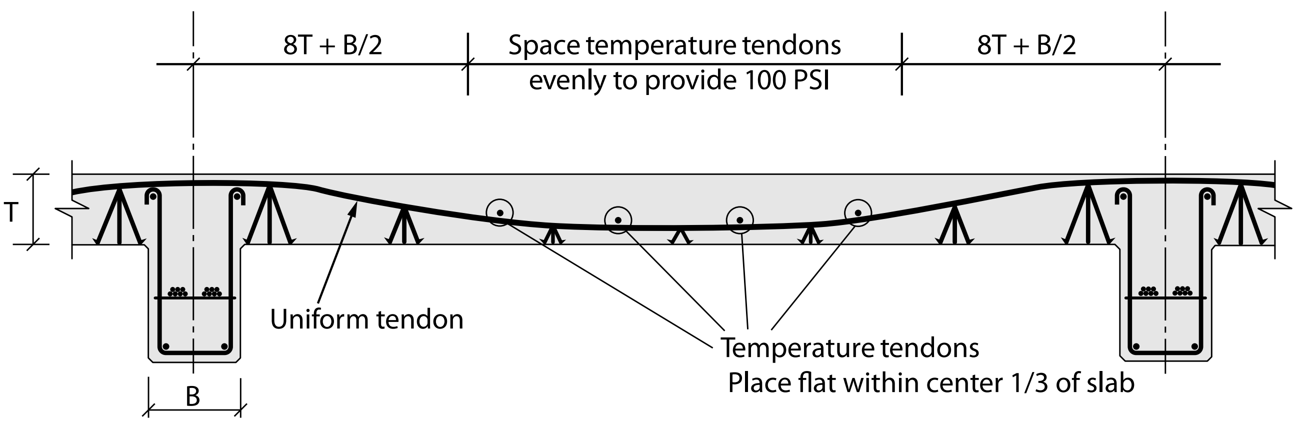


Fig. 2.7.44: While temperature strands may be supported directly on the uniform strands provided in one-way slabs, additional supports may be required to ensure the tendons are within the middle third of the slab. (Image courtesy of PTI).

(dd) As with reinforced concrete beams, the constructability of PT beams can be enhanced by:

- Standardizing beam designs around available formwork systems.
- Consolidate (group) beam designs into the fewest beam marks.
- Detailing beams and girders with out-turned stirrups or open stirrups closed with top caps.

(ee) Avoid excessive congestion that may prevent concrete consolidation at PT anchor zones (Fig. 2.7.45).

Fig. 2.7.45: Congestion in anchorage zones may prevent concrete consolidation. (Images courtesy of PTI.) Stacked and abutted PT tendon anchors indicate the beam width is insufficient for constructability. The most preferable solution would be widening the beam. Additional solutions could include flaring more cables, eliminating embedded items and MEP items in the congested zone, using headed bars or stud rails in lieu of hooked bars, or even using a multi-strand bonded PT system in the beam.

(ff) Two-way PT slabs provide constructable solutions for floors with irregular geometries or support conditions. Banded strands combined (with necessary hairpins) with distributed strands in the orthogonal direction are highly constructable (Fig. 2.7.46).

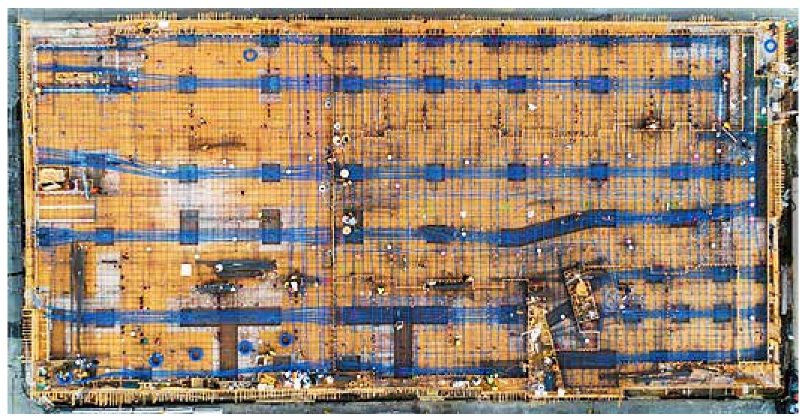


Fig. 2.7.46: An aerial view of a PT floor system shortly before concrete placement. (Images courtesy of PTI.)

(gg) If a project may require future coring of slabs (for example, a hospital or leased office space), a constructable design will use a dual-banded PT system (Fig. 2.7.47). Although such systems are not explicitly permitted by the Code, a dual-banded tendon distribution could be accomplished under the mandate of Section 1.10.1 of ACI 318-19(22).

For additional discussion of dual-banded systems, refer to **PTI Technical Note No. 22 Dual-Banded Post-Tensioning Tendon Layout**.

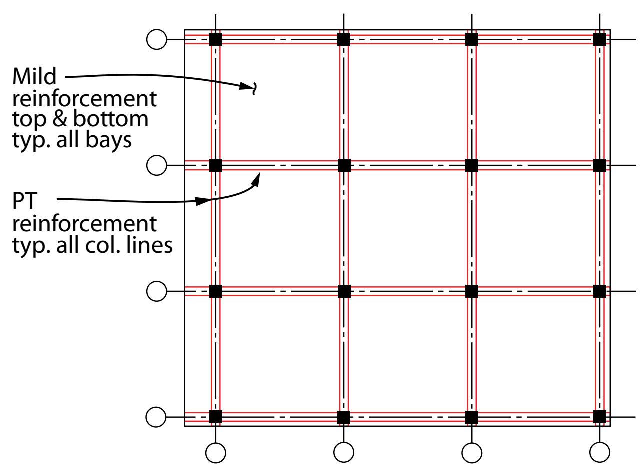


Fig. 2.7.47: A dual-banded PT system will allow large slab regions (reinforced with bars and/or steel fibers) that can be safely cored to accommodate future needs.

(hh) Punching shear is often a challenge for two-way PT slabs. Stud rails are the recommended constructable solution to avoid reinforcement congestion without drop panels (Fig. 2.7.48).

Fig. 2.7.48: Stud rails or double-headed studs can help designers avoid the need for drop panels. (Image courtesy of Amsysco.)

(ii) Two-way PT floor systems often have concentrations of cable anchors. With six or more anchors grouped, bursting steel reinforcement is required per PTI M10.3-16 and ACI 318-19(22). Congestion can be minimized by using stud rails in lieu of hairpin bars (Fig. 2.7.49). Further, headed studs have very effective anchorage and can perform better than conventional hairpin bars (refer to **Headed Studs in Anchor Zones of Post-Tensioned Slabs**). To allow the strand force to transfer into the concrete slab, the anchorage zone of influence must be kept free of MEP conflicts (for example, conduit and sleeves). However, if sleeves and conduit are required within strand anchorage zones, specify the use of Schedule 40 pipe in lieu of the standard material (Fig. 2.7.50).

Fig. 2.7.49: Stud rails can also be used to resist bursting stresses in anchorage zones. The shown headed studs have been instrumented with strain gages to verify their ability to prevent control horizontal splitting at anchorage zones. (Image courtesy of Concrete International, *Headed Studs in Anchor Zones of Post-Tensioned Slabs, April 2005.)*

Fig. 2.7.50: PT anchors adjacent to Schedule 40 sleeves. (Image courtesy of Amsysco.)

(jj) Strands often must accommodate MEP openings or to ensure cables are routed through column cages. Sweeps should be smooth, and hairpins should be included to ensure associated horizontal reactions are securely transferred to the slab (Fig. 2.7.51). If these forces are not properly accounted for, concrete blowouts will occur at nearby openings, requiring rework and associated delays. Podium slabs are generally subjected to high shear forces and often contain thickness transitions and embedded MEP items. Designers should take extra care to focus on details for both constructability and structural integrity.

For example, avoid sweeps at high or low points in tendons, as the reduced cover at such locations increases the risk of blowouts.

(kk) As a designer, provide clear and concise instructions in the construction documents regarding final effective PT forces and the center of gravity profile for the strand. Avoid providing highly detailed drape patterns within bays. Instead, provide key points, as shown in Fig. 2.7.52. Also provide clear guidelines if a stressing sequence or staged stressing is required (note that staged stressing is required when the calculated extreme concrete fiber compression stress exceeds 60% of the specified compressive strength at time of initial prestress f_{ci}' [refer to Section 24.5.3.1 in ACI 318]). For additional guidance, refer to **Top 6 Stage Stressing Questions Answered!**

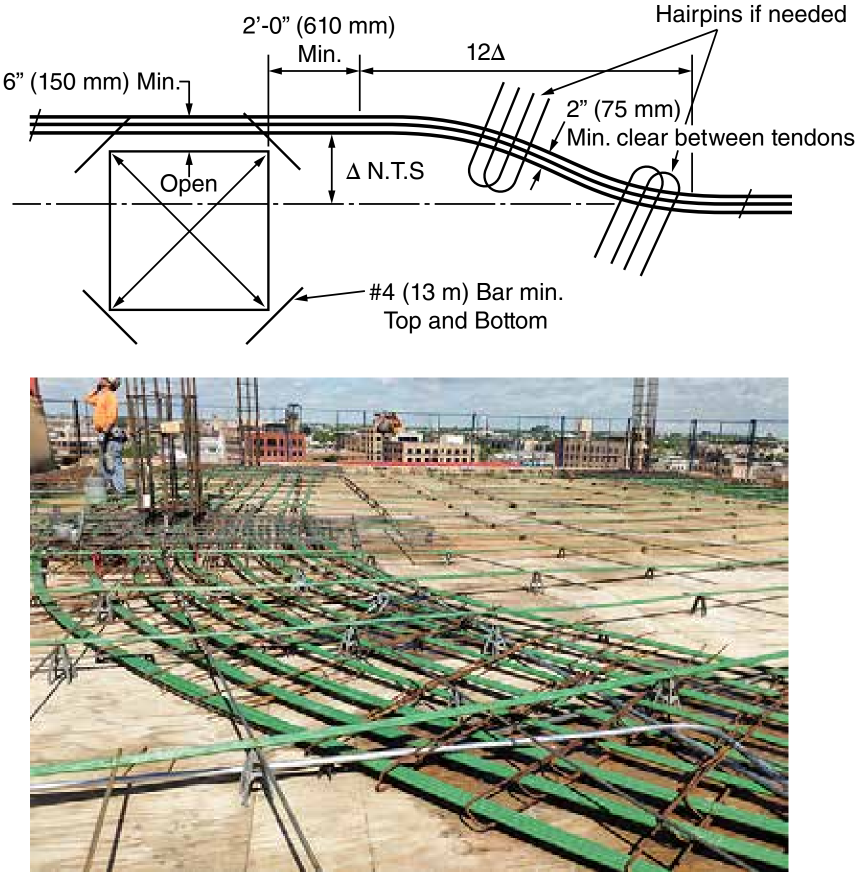


Fig. 2.7.51: Tendon sweeps should be anchored with hairpins if tendons are near slab openings and sleeves. (Diagram and image courtesy of Amsysco.)

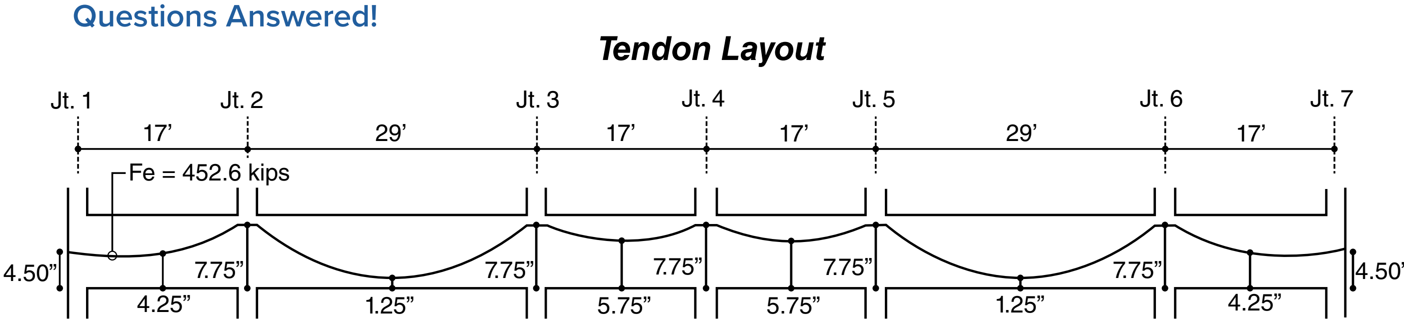


Fig. 2.7.52: Draped strands can provide constructability solutions for transfer girders. Define strand drapes by providing dimensions from the soffit to the strand center of gravity at each support and at midspan of each span. (Image courtesy of PTI.)

(ll) Designers should consider constructability issues when locating PT anchors near walls. Several options are provided in the December 2018 *Concrete International* article, "**Constructability of Post-Tensioning Anchors in Shear Walls**." Figure 2.7.53 provides a detail from that article as well as a photo of PT installation at walls.

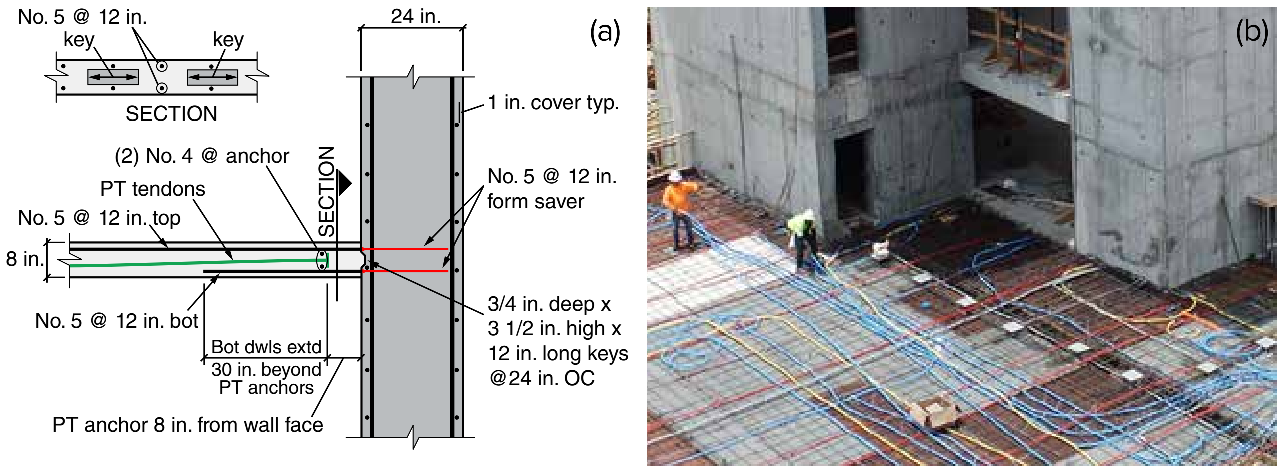


Fig. 2.7.53: A highly constructable option for strand anchorage is to place dead-end anchors near the wall face: (a) a detail from the referenced article; and (b) use of such details allows walls to be constructed ahead of floor structures. (Image courtesy of Ceco Concrete Construction.)

(mm) Designers must avoid confusing the specified compressive strength of concrete f_c' with the specified compressive strength at time of initial prestress f_{ci}'. An f_{ci}' value of 3 ksi is typically driven by the anchorage requirement. Extending curing and delaying strand tensioning beyond the needed f_{ci}' reduces productivity by delaying the cycling of formwork. The use of maturity meters (Fig. 2.7.54) is recommended to monitor and evaluate when f_{ci}' is achieved in real time. Establish a tensioning plan with the contractor allowing strand tensioning to start when f_{ci}' is estimated by the maturity meters.

Fig. 2.7.54: Temperature sensors can be used to monitor concrete curing and estimate the in-place concrete strength. (Image courtesy of Conco.)

(nn) Some jurisdictions require the licensed design professional (LDP) to review all strand elongation reports (recorded by a PTI-certified inspector). In all jurisdictions, the LDP must work with the contractor and PT supplier to resolve the cause if measured elongations differ from calculated elongations by more than 7% (refer to Section 9.3.6.3 of **ACI 301, Specifications for Concrete Construction**). The review and/or resolution of elongation records should be assigned a high priority to avoid delaying the release of formwork. In jurisdictions that do not require the LDP to review all elongation reports, offer the contractor preapproval when elongations are within the specified range. For further information on elongations and elongation records, refer to **Field Elongation Measurements** and **Thoughts Concerning Post-Tensioning Elongation Records**.

Once the LDP has approved the stressing operation, the contractor must:

- Cut the tendon tails within 1 day after approval (Fig. 2.7.55);
- Install encapsulation caps within 8 hours after cutting tails; and
- Grout stressing pockets within 1 day after cutting tails.

(oo) Post-tensioning offers constructable solutions to mitigate cracking. **DC20.2-22: Restraint Cracks and Their Mitigation in Unbonded PT Building Structures**, published by PTI, provides strategies and constructable details to address cracking.

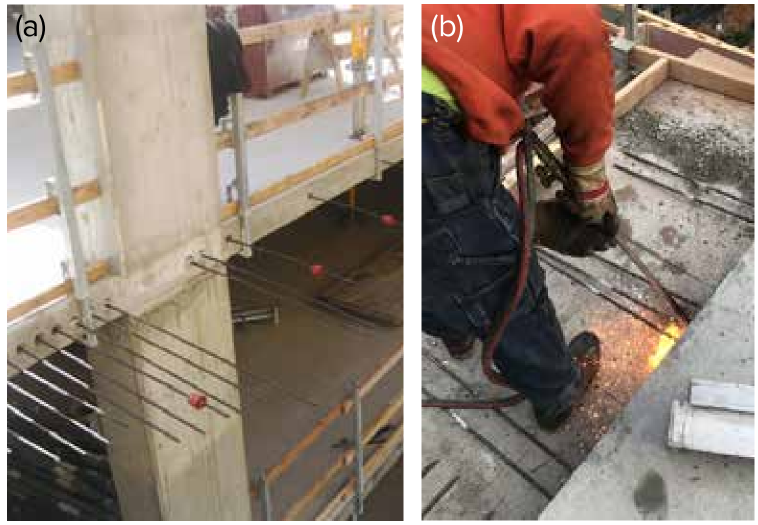


Fig. 2.7.55: PT strand tails must be cut to allow protective systems to be installed at the anchors: (a) strand tails extending from a PT slab (image courtesy of PTI); and (b) a worker cuts a tail using an acetylene torch (image courtesy of Conco).

2.8 MIXTURES, PUMPING, PLACING, AND FINISHING

Designers may overlook how design documents can impact constructability. Here are a few tips to consider for improving the speed of construction, a key element of improving productivity. Start with minimizing the number of concrete mixtures, especially within a single placement area. Changing mixtures is highly problematic when a contractor uses a concrete pump for conveyance, as it is inefficient, wasteful, and time-consuming to clear the pipeline of the initial mixture. For these reasons, adjust designs and mixture criteria to allow slab placements to comprise only one concrete mixture. A good solution is to increase the required strength in the slab to at least 70% of the required strength in columns and walls to eliminate the need for puddling (refer to ACI 318-19, Section 15.5.1). This solution also captures advantages such as enabling earlier strand tensioning and formwork removal while reducing the need for accelerating admixtures to accomplish the same effects. Keep in mind that contractors may seek to tension tendons at a minimum stress of 2500 psi (refer to ACI 318, Section 25.9.4.4), at a more common value of 3000 psi, or at a strength sufficient for the slab to support slab dead loads after tendon tensioning.

At slab concrete strengths approaching 7000 psi, however, also note that finishability can become problematic—especially when the water-cement ratio (*w/c*) is less than 0.40. Although surface-applied retarders can help the contractor finish higher-strength concrete, crews will still be challenged to meet specified floor flatness and levelness requirements, such as F_f and F_l numbers. To avoid inadvertent conflict and loss of productivity, the design team should consider the effects of higher-strength concrete on the tolerances specified in **CSI MasterFormat Division 09: Finishes**. For more discussion of floor tolerances, refer to the article "**Bridging the Specification Gap between Divisions 03 and 09: Concrete and floorcovering associations unite**."

A single mixture should be specified for all vertical elements on a given level. The next best option would be to specify one mixture for the walls and a second for the columns. If puddling is necessary, consider isolating the concrete above the wall or column where higher strength is required. One possible approach is to use a metal mesh (that is, a stay-in-place form) to isolate the floor and column concrete (refer to Fig. 2.8.1(a) and (b)). This solution allows reinforcing bars and strands to be placed through the column while containing the higher-strength column or wall concrete. The designer may consider increasing the concrete cover on the vertical steel to 2 in. to ensure a seat for the slab. Additional shear-friction reinforcement should also be considered, particularly for slabs that do not include post-tensioning strands. Note this approach is not referenced in ACI 318. However, it has been used successfully as allowed per ACI 318, Section 1.10, and the corresponding Commentary.

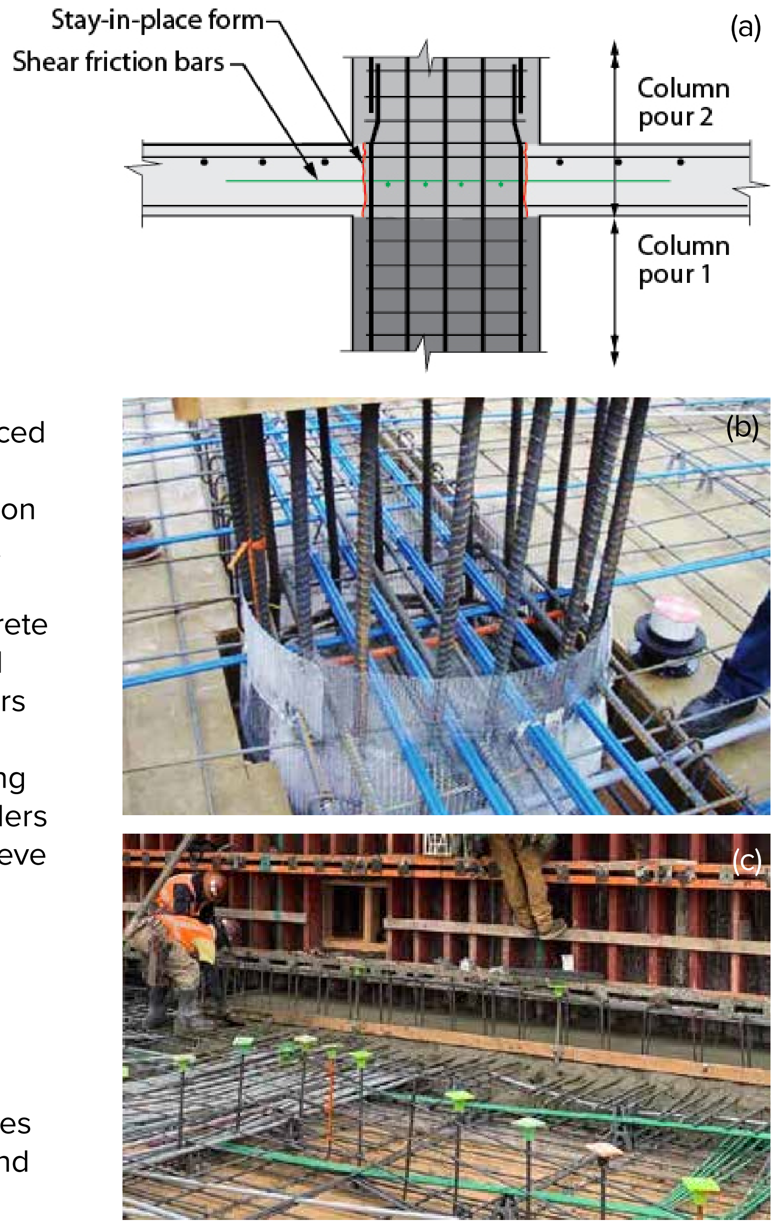


Fig. 2.8.1: Stay-in-place forms can be used to confine higher-strength concrete where it is needed, in the core columns and walls: (a) schematic of column application (image courtesy of CKC Structural Engineers); (b) photo of stay-in-place form at a column (photo courtesy of CKC Structural Engineers); and (c) a high-strength concrete puddle at a wall is confined by a stay-in-place form (located at vertical reinforcement for a future curb and outside the wall plane) (image courtesy of Related).

Concrete materials, properties, and concrete admixture enhancements have advanced greatly, allowing designers and contractors to manage concrete properties during construction and the structure's life. During a collaborative design process, stakeholders may propose innovative materials to achieve project goals. If designing without design assistance from contractors, the best approach is for the designer to specify performance criteria rather than mixture proportions, although some designers may find it necessary to add ranges for material use or admixtures. Concrete varies greatly and should be considered local and dependent upon the capacities of local plants and materials, especially aggregate. Designers should investigate local capabilities early in the design process. However, allowing the contractor, in conjunction with local material suppliers, to design a mixture that meets the designer's performance criteria while embracing the contractor's construction plan greatly enhances constructability by allowing the specification to state only those requirements necessary for each mixture. In other words, the ready mixed concrete supplier is best qualified to determine how to satisfy mixture characteristics that are necessary for design (refer to Fig. 2.8.2).

Fig. 2.8.2: Local contractors and producers will know how to satisfy design objectives as well as placement and finishing requirements for constructability. (Images courtesy of Ceco Concrete Construction.)

Limit the number of different mixtures on a project. While fewer is better, more than a half-dozen should start a review to minimize the number. Contractors' mixture design goals often include strength gain that supports formwork removal needed to meet optimum schedules. Other concerns may include the setting time of a mixture, flowability, workability, and reinforcement congestion. Minimize the need for unique mixtures for stairs and weather-exposed concrete (for example, balconies and plazas). While contractors seek concrete consistency and/or reduced variability, they also must be able to adjust to weather or placing conditions. The contractor may need to adjust mixtures with accelerators and retarders, hot water, or ice. These adjustments are often made just before or during a placement to meet current conditions. Further, pumpability must not be overlooked. When pumping concrete in tall structures, the mixture will likely be incrementally altered with elevation—say, from levels 0 through 20, 21 through 40, and 41 through 80.

Sustainability and embodied carbon quantities are growing design and constructability concerns. The National Ready Mixed Concrete Association (**NRMCA**) has created an excellent reference for total carbon budget decision-making. The approach maximizes the use of supplementary cementitious materials (SCMs) in non-finisher intensive mixtures such as foundations and vertical concrete while minimizing SCMs on post-tensioned (PT) decks and other slabs. In 2023, the *ACI Materials Journal* published another relevant reference: "**Role of Mixture Overdesign in the Sustainability of Concrete: Current State and Future Perspective**," which emphasizes the embodied carbon costs associated with the overdesign of concrete mixtures as a means of risk mitigation. As new materials are developed to reduce the embodied carbon in concrete, mockups and test pours are essential to determine finishability. Even then, contractors will be assuming greater risk as the industry migrates away from ASTM C150/C150M Type I/II cements. Unexpected variability in placing and finishing qualities, for example—even between concrete loads delivered from the same ready mixed concrete plant—have been reported on projects using ASTM C595/C595M Type IL cement.

Concrete sensor technology is advancing rapidly. This technology can improve one's understanding of concrete properties and weather conditions at a given time. Designers are encouraged to embrace and support the use of this technology as a provider of superior information to the owner, designer, contractor, and material supplier. Sensors support informed decision-making that may improve construction productivity and schedule. Such technology, coupled with performance mixture design criteria, may allow the contractor to reduce the quantity of cementitious materials based on the data collected as a project proceeds. Consider reducing the required frequency of testing based on historical methods after sensors have been calibrated and verified.

Additional constructability tips include:

- Ensure that preconstruction meetings (often termed "pre-pour meetings") are scheduled for every project. These meetings should include all concrete stakeholders, including the designer, the owner's testing agency, and all concrete subcontractors. Pre-pour meetings provide opportunities for all stakeholders to develop an understanding of the designer's intent and contractor's plans, so all participants should be open-minded and willing to build project teamwork and relationships. In addition to having a meeting before on-site concrete work commences, another meeting should be held before work begins on elevated concrete elements. Successful meetings will address logistical plans, mixture designs, placing methods, formwork schemes, potential constructability issues, and the potential for hot-weather and/or cold-weather concrete placements (and consequent mixture designs). They will also address the impacts of the mechanical and electrical subcontractor's work on the concrete contractor's operations; concrete testing procedures and information flow; tolerances on concrete elements; and the concrete contractor's plans for conveyance, placing, finishing, and curing. Lastly, meeting goals should include the identification of necessary mockups, test pours, and material submittals.

- Sampling and acceptance testing for concrete properties such as slump and air content are best conducted at the point of delivery (truck discharge—refer to Fig. 2.8.3). As stated in ASCC Position Statement #20, "Testing fresh concrete at the point of delivery is safer for the technician, typically provides a more stable and comfortable work area to ensure that ASTM testing standards are met, and results in a more continuous flow of concrete that minimizes the potential for concrete segregation and cold joints." However, as stated in the Optional Requirements Checklist for Section 4.2.2.4 of ACI 301, "It may be necessary to specify that air content be measured at the point of placement to account for loss of air content during pumping. Once the loss of air content during pumping is established, acceptance limits at the point of delivery can be determined." The impact of pumping can then be reflected in acceptance criteria at truck discharge. For more information, refer to **ACI 301-20** and **ASCC Position Statement #20**. Also refer to the text accompanying Fig. 2.13.7 in this document.

Fig. 2.8.3: Technicians conduct concrete testing (slump and air content) at the point of delivery. (Image courtesy of The Conco Companies.)

- Understand where floor flatness F_F and floor levelness F_L testing (refer to Fig. 2.8.4) are applicable and appropriate (refer to Table 2.8.1 for typical uses). Do not over-specify performance levels or areas, as excessive quality requirements hinder constructability and are not cost-effective. Testing often deters construction tasks as the concrete surface must be kept clear of construction materials until testing is completed. Eliminate the need for testing when results are not critical to avoid the likelihood of extending construction schedules to accommodate the testing task. Noncritical applications are those with $F_F < 30$ or $F_L < 20$, as well as slab surfaces that are sloped or cambered.

Fig. 2.8.4: Floor flatness (F_F) and floor levelness (F_L) testing is conducted within 72 hours after concrete placement and before shoring of supported slabs is released or strands are tensioned in PT slabs. Per ASTM E1155, levelness (F_L) is not a standard that is tested on unshored elevated/suspended slabs. (Image courtesy of Hensel Phelps.)

- Advances in concrete placing technology of slabs-on-ground have enhanced constructability and speed of construction by allowing larger placements and fewer construction joints. Designers should be aware that contractors will seek to capture the advantages of a laser screed on placements exceeding 20,000 ft^2 in area.

Table 2.8.1: Typical flatness and levelness guide (after ACI 302.1R-15, "Guide to Concrete Floor and Slab Construction")

Composite overall flatness, F_F	Composite overall levelness, F_L	Typical use
20	15*	Noncritical: mechanical rooms, non-public areas, surfaces to have raised computer flooring, surfaces to have thick-set tile, and parking structure slabs
25	20*	Carpeted areas of commercial office buildings or lightly-trafficked office/industrial buildings
35	25*	Thin-set flooring or warehouse floor with moderate or heavy traffic
45	35†	Warehouse with air-pallet use, ice or roller rinks, gymnasium floors
>50	>50†	Movie or television studios

*F_L applies only to slabs-on-ground or suspended slabs shored at the time of testing.
†F_L applies only to slabs-on-ground or suspended slabs constructed using two-course placement.

- Tips for horizontal concrete include:
  - Larger slab-on-ground placements should anticipate 70 ft placement widths to optimize laser screeds.
  - As horizontal concrete becomes thicker (>24 in.), it becomes difficult for crew members to safely place the concrete without stepping into gaps between bars. Designers can improve working conditions by adding a single layer of 6 x 6 in. welded-wire reinforcement (provide additional cover to accommodate the wire grid) or a grid of No. 4 bars at 12 in. on-center

on top of the reinforcing bars. The mesh provides standing support and significantly reduces the probability of injury (refer to Fig. 2.7.15).

- Cast-in-place vertical reinforcing bars for curbs, low walls, and capads are difficult to place and maintain in alignment, present obstructions to finishing (resulting in lower floor profile numbers), and are safety hazards. Specifications and details should allow dowels to be installed in a slab using adhesive anchors (refer to Fig. 2.8.5).
- Focus on a concrete mixture that flows laterally if it is impossible to deposit concrete in its final position. The concrete mixture must be designed with admixtures to flow at least 10 to 15 ft laterally without segregation. This is likely to require self-consolidating concrete (SCC). Section 4.2.2.2 of ACI 301-20 instructs the contractor to submit the target slump flow, noting that this target will be used as the basis for acceptance during the project. Meeting this requirement will help ensure that concrete encases congested reinforcement, lap splices, and embedded items and can flow around blockouts.
- Note that ACI 301, Section 4.2.2.3, requires that the nominal maximum size of coarse aggregate must be no larger than 3/4 the minimum clear spacing between bars, 1/5 the narrowest dimension between form sides, or 1/3 the thickness of slabs or toppings.

Fig. 2.8.5: Construction of a curb. Dowels have been installed by drilling and setting in adhesive anchors, and the formwork has been installed. (Image courtesy of Hensel Phelps.)

Fig. 2.8.6: An example of a beam with large coarse aggregate, inadequate cover, and spacing between bars. (Image courtesy of Ceco Concrete Construction.)

- Ensure adequate cover and bar spacing in the beam for concrete to flow between bars and between bars and formwork (refer to Fig. 2.8.6).
- Polished concrete requires special consideration, as a polished concrete slab must have a high degree of flatness (refer to the article "**Specifying Polished Concrete Floors**"). This is difficult to achieve on suspended slabs due to elevation tolerances and movements resulting from post-tensioning and deflection after the removal of shoring. The structural engineer should consider increasing the slab stiffness. Further, it may be prudent to specify an additional 1/2 in. of top cover in anticipation of grinding loss of cover. Additional information can be found in this article: "**Why Polishing Suspended Concrete Slabs is More Likely to Disappoint Customers**." For additional resources, refer to the website of the **Concrete Polishing Council** of the American Society of Concrete Contractors (ASCC).

- Tip for vertical concrete:
  - For vertical concrete elements, avoid specifying maximum free-fall distance for concrete placements. Assume that concrete will be discharged from a hose or concrete bucket at the top of the formwork. Studies presented in a *Concrete International* article ("**Free Fall of Concrete**") show that: "Free fall of concrete from heights of up to 150 ft (46 m) directly over rebar or at high slumps, does not cause segregation, or reduce compressive strength [emphasis in original]." While **ACI 237-07(19)**, Section 1.4, provides concerns regarding the potential for segregation, specification of techniques to minimize the effects of concrete free fall will result in unnecessary and unproductive labor expenses without benefiting the in-place quality of the concrete.

2.9 LOGISTICS, HOISTING, AND SAFETY

Before any concrete contractor commences a project estimate, schedule, or proposal, the first step is to assess the project logistics. The contractor will consider the project design and its location on the project site as well as envision the accessibility of labor, construction equipment, and materials. The thought process will expand to the structural framing, as the contractor will consider the most efficient formwork options, the weight and movement of forms, and the convenience of materials delivery. The construction documents are reviewed in detail, especially the site plan. Local constraints are considered, and the contractor will ask project ownership about the scheduled start and completion goals as well as the anticipated pace of construction. Investigations are made into possible crane locations, concrete placement sizes, possible on-site staging of materials and equipment, and the potential opportunities for preassembly of components such as reinforcing bar cages. Other questions will include: What are the potential crane loads, the necessary reach of the crane, the number and rate of crane pick cycles, and lines of operator visibility?

Adjacent properties are examined to assess potential crane movement beyond the property lines, the risk to adjacent property and pedestrian exposure, and road accessibility and site access. Distances to ready mixed suppliers, travel time, and plant quality and capacity are determined to support a workable logistics, construction, and safety plan. Only when a plan is in place can a meaningful project estimate or schedule be created. However, it may be said that a project schedule (production) is always limited by the logistical planning of crane availability, assembly, and conveyance of materials.

Consider the following constructability logic:

(a) High-productivity formwork systems can be heavy when configured as large, prefabricated panels. If the structural system is sufficiently repetitive to justify the use of panelized formwork systems, sufficient crane capacity and reach are required to capture the full potential productivity gain. The selection of the crane type and size is interdependent with the weight of the formwork system as well as the crane location and crane hoisting radius (refer to Fig. 2.9.1). This is a delicate optimization challenge for the contractor, as the crane expense increases with capacity and hoisting range.

Fig. 2.9.1: A tower crane is used to lift a slab form. The center of such a load can be 30 or 40 ft beyond the face of the building. (Image courtesy of Hensel Phelps.)

The most efficient crane solution has the crane located near the heaviest crane pick. The size and location of the crane will depend on the available area and suitable soil conditions for the crane foundation. For the most productive results, consider:

1. Locating longer shear walls (a structural element that is likely to require the heaviest formwork pick seeking maximum productivity potential) near potential crane access areas will reduce the size of the crane needed. If load and reach requirements exceed crane capacity, the only solution available to the contractor is to reduce form size (to reduce lift weight). If the designer considers or is aware of potential construction crane operational areas, include those options on the site plan.

2. Although mobile cranes require less site preparation and can cost less than tower cranes, many urban project sites are too restricted for mobile cranes to access the required load locations. Mobile cranes achieve load pick reach by lowering the boom, and this maneuver is often restricted or limited.

3. Site constraints and crane reach to load location often demand a tower-type crane. While there are several types, functionalities, capacities, and reaches, most tower cranes require a significant foundation (either a large mat or supported by piles) to enable their performance (refer to Fig. 2.9.2). The location of a tower crane may be limited to areas accessible by the mobile cranes used to erect and dismantle the tower crane (refer to Fig. 2.9.3). If so, the location of the heaviest load becomes the determining factor for the size and reach required for the tower crane, while the crane selected becomes the limiting factor for the construction equipment productivity potential. The most cost-effective solution for a tower crane foundation is to consider the need when designing the structure foundations and incorporating the load needs during the construction period. A tower crane and its loads are temporary and often significantly less than the building load on foundations. Typical tower crane foundation loads can range from 200 to 500 kip of downward force and 50 to 150 kip of uplift. Tower crane

Fig. 2.9.2: A tower crane foundation. (Image courtesy of The Conco Companies.)

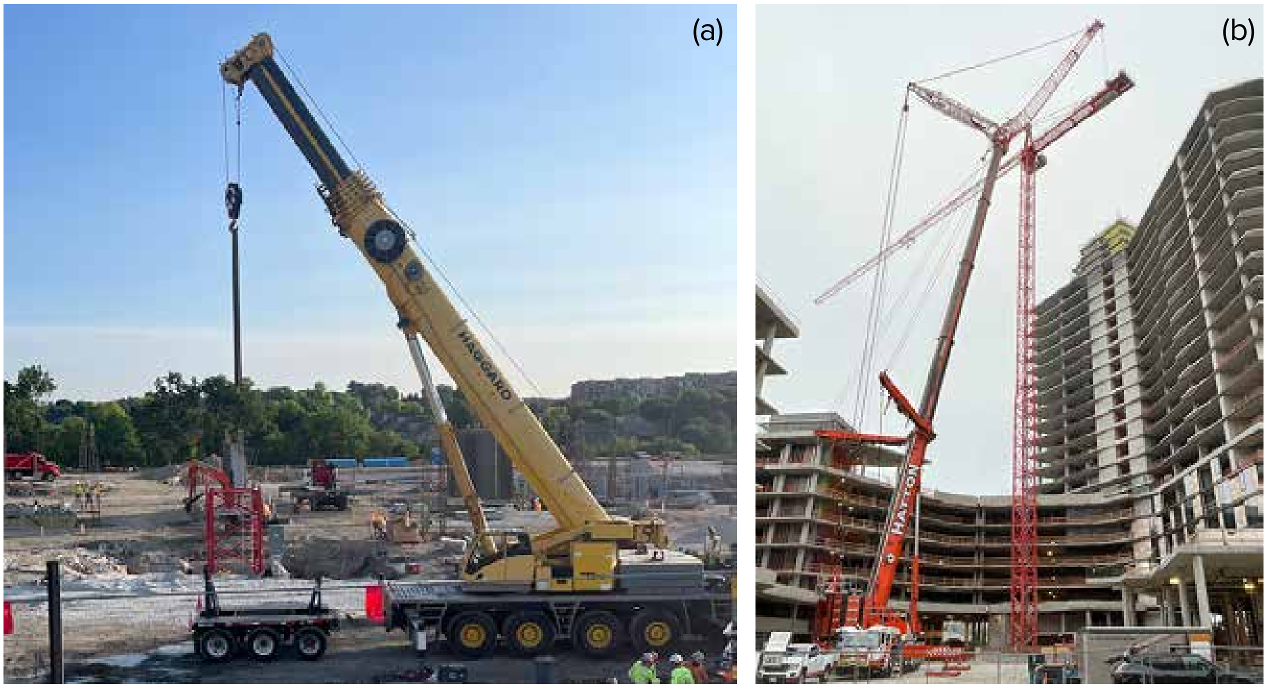


Fig. 2.9.3: Assist mobile cranes require space to erect and assemble tower cranes. Access for the assist crane to disassemble the tower crane must be considered at the conceptual design stage to ensure access after the structure has been completed. (Images courtesy of (a) Ceco Concrete Construction and (b) Related.)

installations can vary with the specific model, crane configuration, foundation scheme, and geometry, all of which will impact the magnitude of foundation reactions. Tower crane foundations demand a specific design review by a licensed engineer. A tower crane and the operational loading will be dismantled and removed before building occupancy.

4. Although tower crane foundations may need to be large, contractors will strive to ensure they fall below the threshold of a "mass concrete structure" (refer to Fig. 2.9.4). Mixtures designed for mass concrete will generally have slow strength gain to limit the heat of hydration, and most tower crane erectors will seek confirmation that the concrete has reached 85 to 100% of the foundation design strength before crane erection. Because

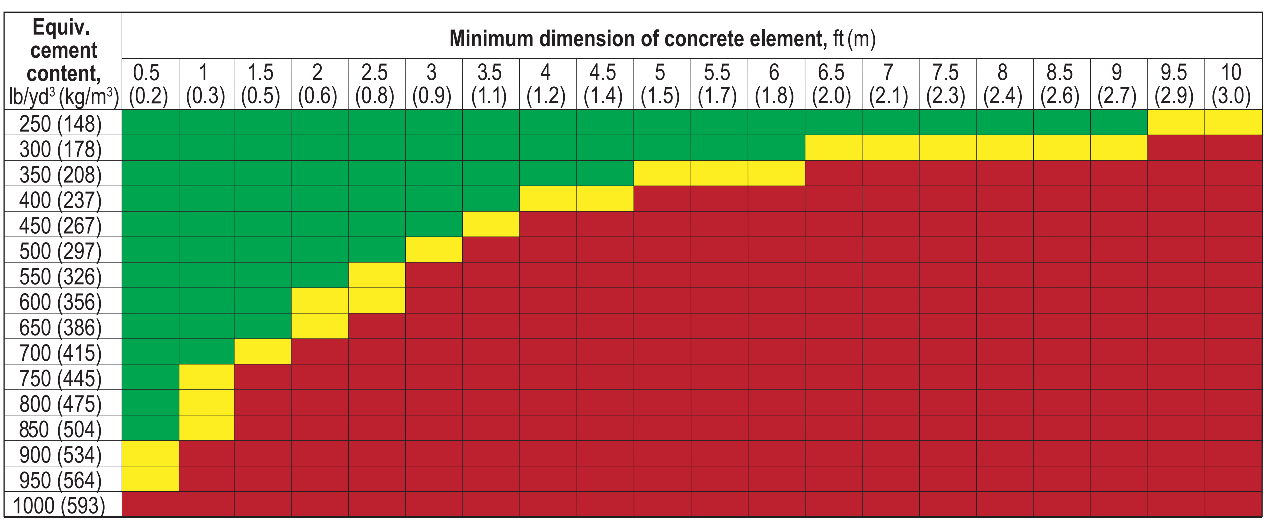


Fig. 2.9.4: A design aid for evaluating the need to treat a placement as mass concrete. Refer to ***ACI PRC-207.1-21, "Mass Concrete—Guide,"*** *for the definition of the equivalent cement content.*

the tower crane foundation is on the critical path for many projects, designing it as a mass concrete structure could result in an extended project schedule. A cantilevered grade beam from an existing foundation element is often a good solution.

Tower crane foundations are often one of the earliest concrete pours and may be an opportunity to test-pour a critical mixture design that will be used later in the project.

5. On taller projects, large core walls have structural benefits. If the core wall formwork can be sufficiently reused, then a self-climbing hydraulic lifting system becomes cost-effective and is productive (refer to Fig. 2.9.5). This solution also decreases demand for the tower crane's availability and capacity, thereby improving the impact on productivity.

Fig. 2.9.5: A self-climbing formwork system topped by a work/storage platform and a placing boom. The entire system is lifted by hydraulic jacks from embeds in previously poured walls below the system. (Image courtesy of The Conco Companies.)

(b) The contractor's plan for the conveyance of concrete should also be considered in the design stage. There are two primary solutions for conveyance: crane and bucket, or concrete pumps. The industry has generally shifted toward concrete pumps as the most productive solution that also reduces the demand on a crane's availability and capacity. A mobile concrete pump that reaches the placement area is generally the most productive. However, such concrete pumps can require a 30 x 30 ft area to stage the pump with the outriggers extended for stability, and an adjacent area of 24 x 30 ft can be required to stage the concrete trucks at the concrete pump during discharge. Site conditions affect conveyance productivity in the following ways:

1. A concrete pump location should allow access by two trucks to allow nearly continuous discharge (refer to Fig. 2.9.6). If site space limits only one truck to be staged at the concrete pump, then the pumping productivity is cut by more than 50% and concrete placement time doubles.

Fig. 2.9.6: A concrete pump on a tight site accommodating two mixer trucks. (Image courtesy of Ceco Concrete Construction.)

2. If space limits the staging area, a smaller pump (trailer pump) can be used to deliver concrete through a "slick line" concrete hose (Fig. 2.9.7). While a trailer pump eliminates the area needed for pump truck outriggers (Fig. 2.9.6), the hose must be manually dragged throughout the placement area—this is a labor-intensive process and can reduce productivity by more than 50%. An alternative solution is to use a smaller trailer pump coupled through a "standpipe" to a placing boom. While the standpipe can be accommodated in the building core (refer to Fig. 2.9.4), some structures may require a floor slab opening to allow for the vertical conveyance of concrete (refer to Fig. 2.9.8). This should be considered during the design phase. Note that an elevator shaft opening is not a good solution, as it is critical that the elevator installation process be started before the removal of the concrete standpipe.

3. While placing booms reduce the labor required to place concrete, they have limited reach. A project may require standpipes, pedestals, and booms at multiple locations.

4. If a project's site is restricted, a workable solution is to place the trailer pump within the footprint of the structure. Again, space will be required for the pump, and it must be accessible by two concrete mixer trucks (refer to Fig. 2.9.9 and 2.9.10). In both cases, loads imposed by the trucks, pump, and fresh concrete must be considered when designing the supporting slab.

(c) Concrete construction in urban areas results in multiple logistical issues, and addressing them during the conceptual design stage may impact productivity. Here are a few issues for consideration:

Fig. 2.9.7: A trailer pump with slick line. Access for two concrete trucks remains critical for concrete placing productivity. (Image courtesy of Ceco Concrete Construction.)


Fig. 2.9.8: A placing boom coupled to a standpipe accommodated through a blockout in the floor slab. In this photo, the placing boom is mounted on a pedestal and anchored to the floor slab(s). These construction loads in the floor slab should be considered prior to installation. (Image courtesy of Ceco Concrete Construction.)

Fig. 2.9.9: A trailer pump positioned within a structure can convey concrete through a "standpipe" to the levels above. (Image courtesy of Ceco Concrete Construction.)

1. Material deliveries require space for staging full-sized semi-tractors and trailers while unloading and loading. Providing adequate paths for ingress, loading, and egress is critical and may be a driving factor in the sequencing of construction, speed of construction, and location of expansion or construction joints.

2. Consider localized construction loads for equipment, including concrete pumps, staging of formwork and reinforcement, forklift use, or stockpiling tenant improvement materials such as drywall and flooring tile (refer to Fig. 2.9.11). Building these loads into the design with additional reinforcement will reduce temporary reshoring needed to accommodate the loads. This can improve constructability further by opening lower areas earlier for finishing trades. Material is often stockpiled on a slab that is open to crane access. Typical areas include podiums, balconies, or building setbacks. Figure 2.9.12 illustrates an area where the staging of formwork and reinforcement occurs on the top deck of the base structure.

3. Construction sites may be adjacent to properties with restrictive air rights, or they may represent safety risks to inhabitants or pedestrians. These conditions will preclude the movement of crane loads above the property or public accessways, and they may require the use of advanced construction protective screening systems, sometimes called "cocoon systems," as shown in Fig. 2.9.13 and 2.9.14.

   As shown in Fig. 2.9.14, these systems require embedded anchors to transfer forces from perimeter support arms to the slabs enclosed by the screen. The required anchors may conflict with slab shear reinforcement adjacent to perimeter columns. Also, the support

Fig. 2.9.10: A boom pump and two concrete trucks delivering concrete from a position on top of a previously constructed deck section. (Image courtesy of Ceco Concrete Construction.)

Fig. 2.9.11: Material will be stockpiled on decks, and these loads should be considered during design. (Image courtesy of Related.)

Fig. 2.9.12: Formwork and reinforcing bars for the tower in the background are being staged on top of the base structure in the foreground. (Image courtesy of CKC Structural Engineers.)

Fig. 2.9.13: Examples of protective screening systems: (a) an aerial view of a cocoon during a concrete pour (image courtesy of Ceco Concrete Construction); and (b) a street view of a cocoon segment during installation (image courtesy of Related).

arms may restrict the constructability of perimeter shear walls or cantilevered slabs and balconies if their profiles are not consistent and repetitive upward.

4. All too often, project designs place the perimeter enclosure at the property line. Such designs make it impossible to construct a building without encroaching on the neighboring property. If designing a project adjacent to another building, designers should allow a 6 to 12 in. setback to allow formwork and labor access. If a slab is post-tensioned and it is not possible to place the tensioning (live end) anchors away from the adjacent structure, a 30 in. gap is required between the slab edge and the adjacent structure to provide room for tensioning jacks. Addressing these considerations during design prevents a decline in construction productivity.

(d) Many larger projects are designed to achieve multipurpose use. They often will have a larger footprint base structure topped with a smaller footprint multi-story tower, as shown in Fig. 2.9.11. The productivity tip to consider as a designer is the separation of the tower footprint from the base structure footprint. There are advantages beyond contractor productivity. The two areas may have

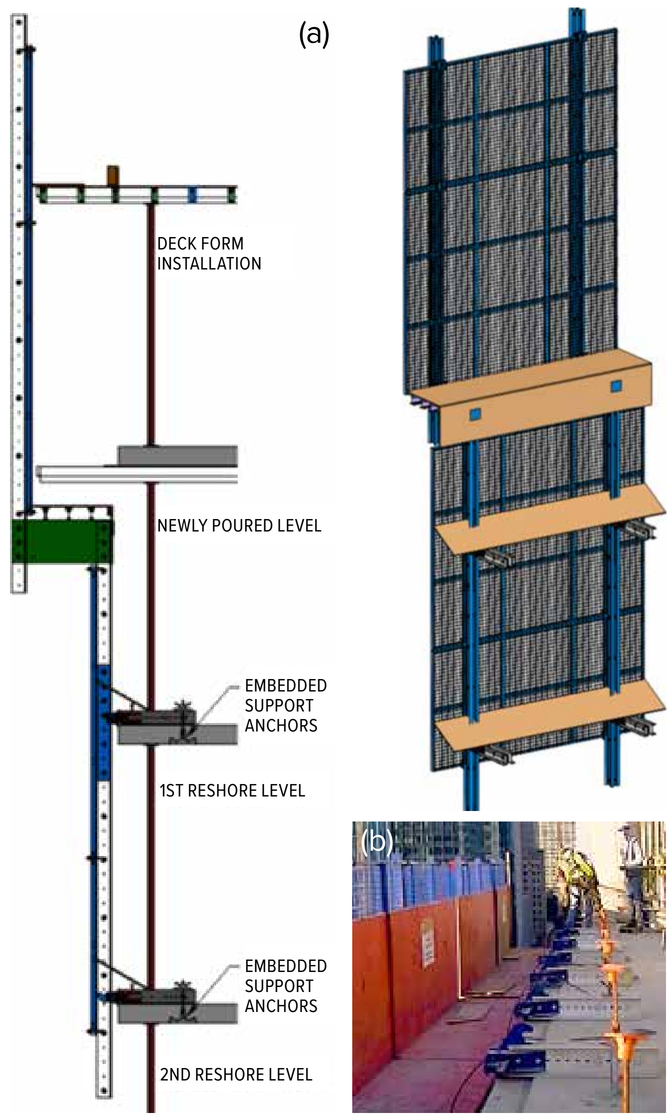


Fig. 2.9.14: Protective screening systems must be anchored to recently cast decks: (a) schematic of a system anchored at the first and second reshore levels; and (b) support arms and anchor rods at the edge. (Image courtesy of Ceco Concrete Construction.)

different foundation designs as well as settlement, creep deformation, or temperature exposure behaviors. By isolating the two areas, induced forces and associated cracking can be minimized. Consider isolating the smaller footprint from the base structure by means of an expansion joint on the levels that would otherwise be continuous between the two areas. On such projects, the critical path of the contractor's schedule is typically the tower and elevator installation that follows the concrete contractor (refer to Chapter 2.6). The separation provides site space for the contractor to mobilize and focus on the tower footprint to expedite its completion in less time—a constructability enhancement that shortens the schedule. Once the tower concrete construction is fully mobilized, equipped, and proceeding, the contractor can initiate work on the base structure outside the tower footprint. The use of the expansion joint supports the plan and simplifies the process compared to multiple levels of construction joints seeking to accomplish the same goal.

(e) To advance productivity, contractors often seek to place larger concrete pours during nontraditional work hours (Fig. 2.9.15). There is less road traffic, so material delivery timing is more predictable. As a result, placement rates and pour sizes can increase. Often, the quality of the work improves, as curing occurs when the heat of the sun is less intense. Unfortunately, there are barriers to this productive step. Those barriers include labor restrictions, local work time or noise restrictions, the need to provide ample lighting, scheduling pre-placement engineering and building department inspections, or third-party testing limitations. To boost productivity, consider supporting the contractor's efforts to overcome these barriers, including increasing designer and inspection fees or cost allowances to achieve the contractor's goals of pouring during nontraditional work hours. For every 6-hour placement that can be shifted to nontraditional work hours, the project schedule will likely be shortened by 1 day—a tremendous productivity gain!

Fig. 2.9.15: Examples of night placements. (Images courtesy of Ceco Concrete Construction.)

(f) On almost every project, inconsistent sampling and other procedural errors result in poor air content, slump, or strength test results that impact construction productivity. Delays in distributing test reports to all stakeholders, including the ready mixed concrete supplier, also can impact a project, as investigations of results are often outside the contractor's control but have large financial risks that drive unproductive contractor solutions to mitigate the risks. Technology is evolving to reduce or eliminate historical, manual, and inconsistent test procedures. Designers should consider allowing technologies such as embedded sensors to be used for acceptance, as such systems can make data available to all stakeholders in real time.

2.10 VERTICAL ELEMENTS

Consider the load path of gravity loads through the structure in Fig. 2.10.1. A continuous load path from the roof to the foundation improves constructability with the consistency of members and formwork systems. Avoid transfer beams where possible.

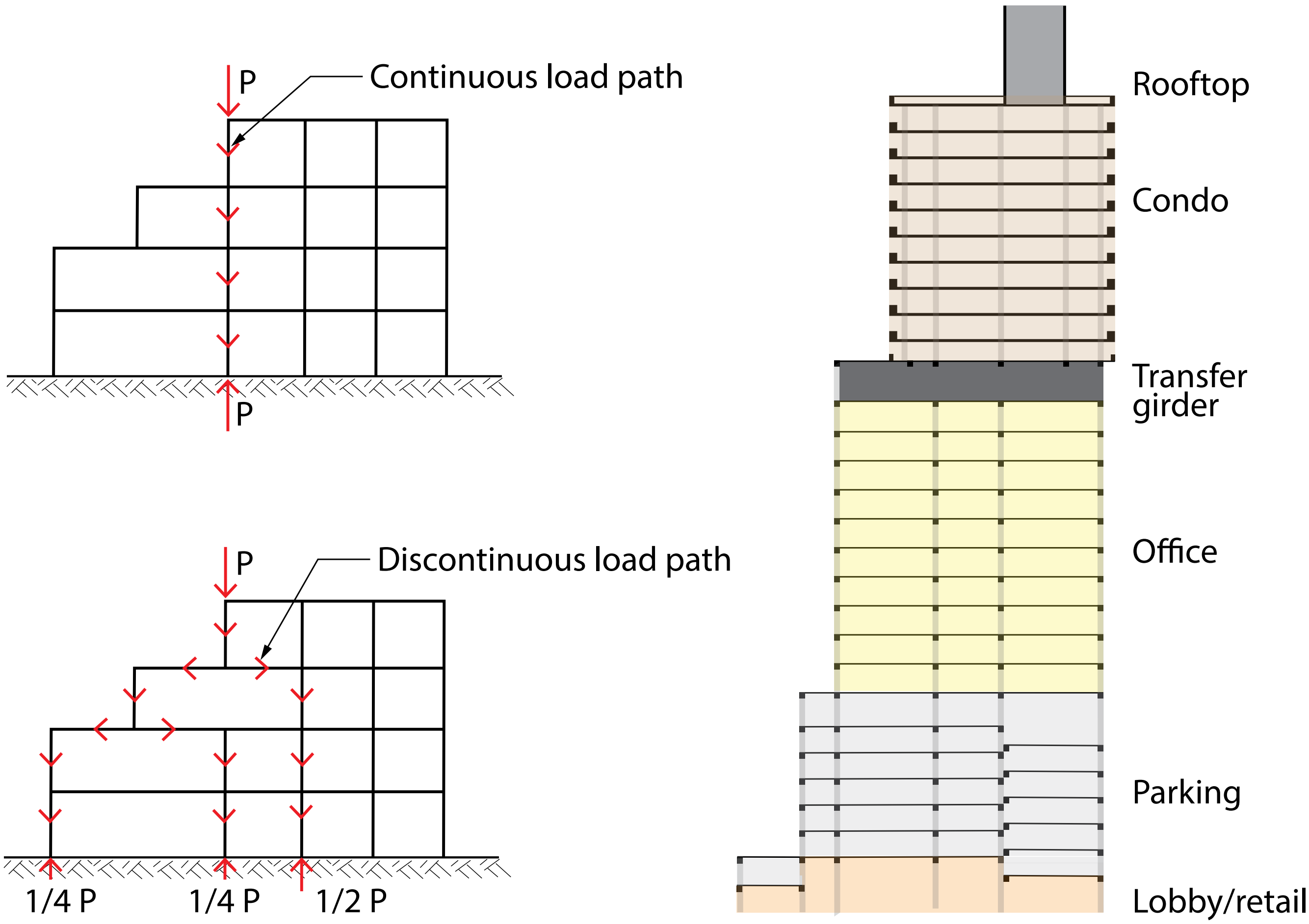


Fig. 2.10.1: Continuous load paths improve constructability and efficiency by allowing repetitive member designs. (Image courtesy of CKC Structural Engineers.)

Keep in mind that when designing columns and walls, less is best, and consistency in size or shape is key. While columns are more constructable than walls, wall constructability can be enhanced through the use of crane-lifted gang forms or self-climbing wall forms (refer to Fig. 2.10.2 and 2.9.4).

Walls will generally be sized to accommodate the forces imposed at the lower levels of a structure. As gravity and lateral loads reduce on subsequent floors, maintain efficiency by making the following sequence of modifications:

1. Decrease the reinforcement percentage;
2. Reduce the concrete strength;
3. Decrease the reinforcing bar size;
4. Reduce the wall thickness (per Fig. 2.6.14); and
5. Decrease the length of the wall.

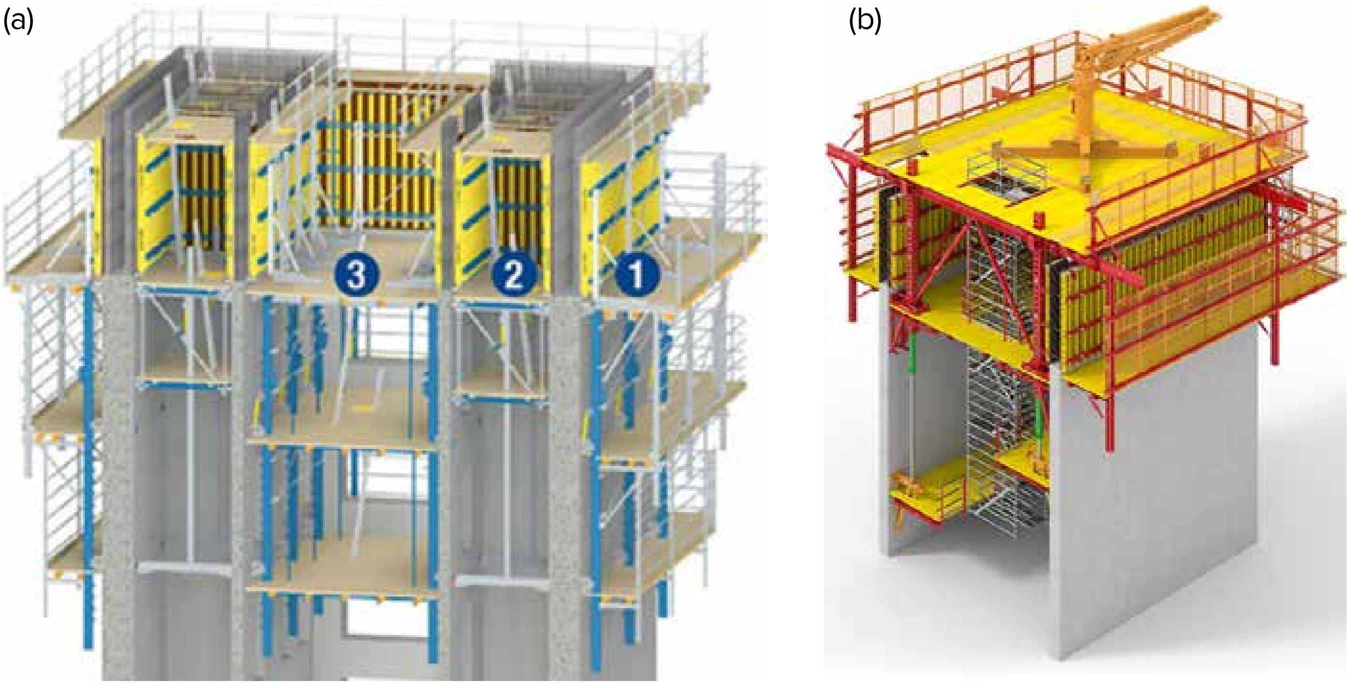


Fig. 2.10.2: Schematics of self-climbing wall formwork systems. Hydraulic jacks used to lift the formwork are connected to anchors in recently placed concrete below. These anchors may necessitate requests for modifications to reinforcing bar layout: (a) the numbers on this system indicate a lifting sequence to accommodate the installation of reinforcement; and (b) this system is capable of lifting inner and outer forms and work platforms simultaneously. (Images courtesy of Doka and PERI.)

The same recommendations apply to columns, although modifications 4 and 5 will be replaced with:

4. Change the column size.

Always avoid wall pilasters—contain columns within the wall instead (refer to Fig. 2.6.10). If a specific column size is only sparsely required, a round column design is preferred—inexpensive, single-use, disposable round column forms eliminate the labor required for form assembly.

Standardized formwork sizes:

(a) Rectangular columns: Increase in 2 in. increments starting at 18 in. Realize that once a column side exceeds 30 in., the pressure imposed by the concrete will require stronger formwork and/or a tie rod through the column. This encourages the designer to stay below 30 in. or make fewer size changes above 30 in. to allow formwork reuse to justify a stronger/heavier gang form and needed hoisting assistance for handling.

(b) Round columns: Increase in 6 in. increments starting at 12 in. diameter. Single-use formwork will be structural fiberboard, and multiple-use formwork will be fiberglass or steel, with the latter likely when the diameter exceeds 36 in.

(c) Wall thickness: 8 in. minimum, 2 in. increments until 18 in., and 6 in. increments thereafter.

Core wall design that encompasses vertical elevators requires the designer to pay attention to vertical tolerance coordination. Often, elevator designs require concrete construction tolerances that exceed ACI recommendations. This can be unproductive, as concrete construction may not be able to achieve such results. At the very least, the designer should be clear in the documents as to this tolerance expectation. Oversizing wall openings and planning for later filling to the needed door, window, or MEP dimensions offers the benefit of fewer tolerance conflicts among field teams. On many projects, wall opening information is not available when concrete formwork planning is necessary, making this a good solution. Openings can be reduced using cold-formed steel or masonry (refer to Fig. 2.10.3).

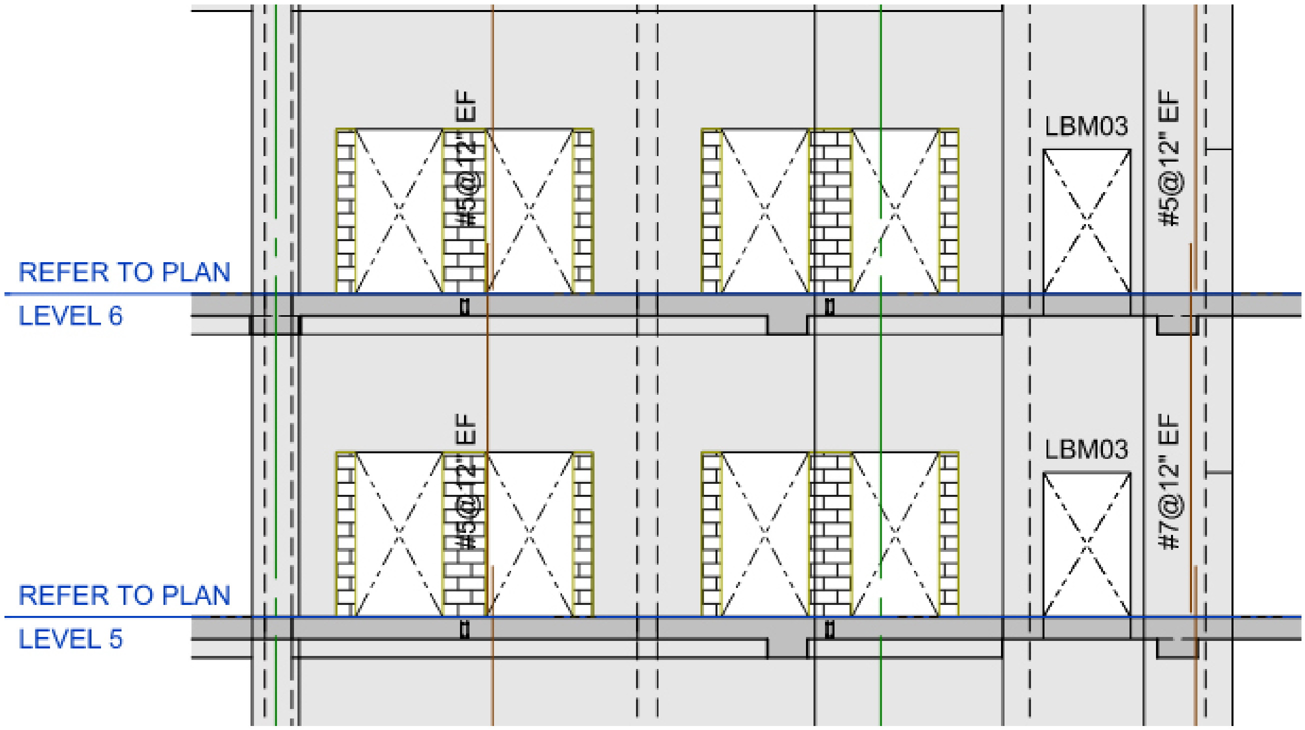


Fig. 2.10.3: Concrete masonry units can be used to create multiple openings from one large blockout in a concrete wall. Note that replacement of multiple small openings with fewer larger openings will require coordination of structural and architectural plans. (Image courtesy of Ceco Concrete Construction.)

Minimize wall face disruptions in all walls, specifically foundation walls, to achieve the best constructability. Compare the diagrams in Fig. 2.10.4. Assume each plan represents the same lineal wall footage to be formed. There is a direct proportion between the number of changes in formwork direction (or plane) and labor cost or loss of productivity. Plan A is the most constructable and allows the consideration of gang-form use. Plan E is the most labor-intensive, costliest, and least constructable, with seven wall-form planes. Avoid Plan B of thinning/thickening the wall; instead, seek to modify reinforcement. Plans C and D are good solutions without a pilaster, especially if all wall directions are extensive in length.

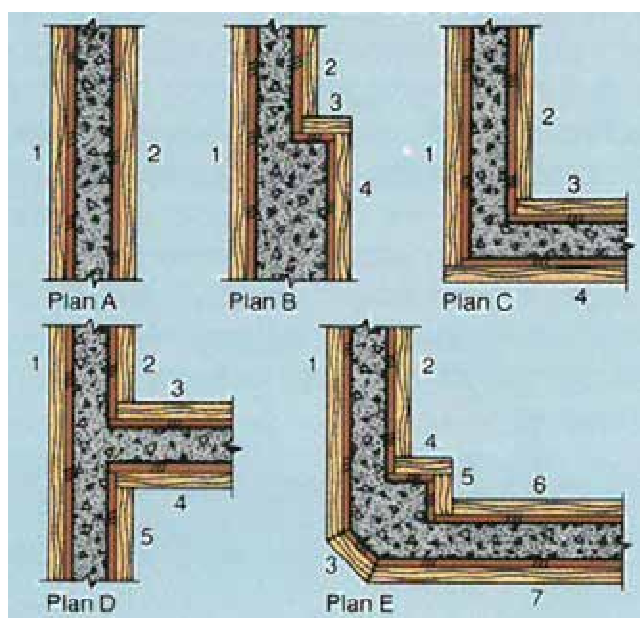


Fig. 2.10.4: Maintain consistent planes in formed wall surfaces to optimize constructability. (Image courtesy of Ceco Concrete Construction.)

2.11 LATERAL-FORCE-RESISTING SYSTEMS

Lateral-force-resisting systems for concrete structures should be evaluated for constructability. There are two main approaches: shear wall or rigid frame. Both have advantages and constructability challenges. However, other hybrid (dual system), novel, and innovative approaches exist (refer to Fig. 2.11.1). When those are considered, contractor-designer collaboration is highly recommended by PRO.

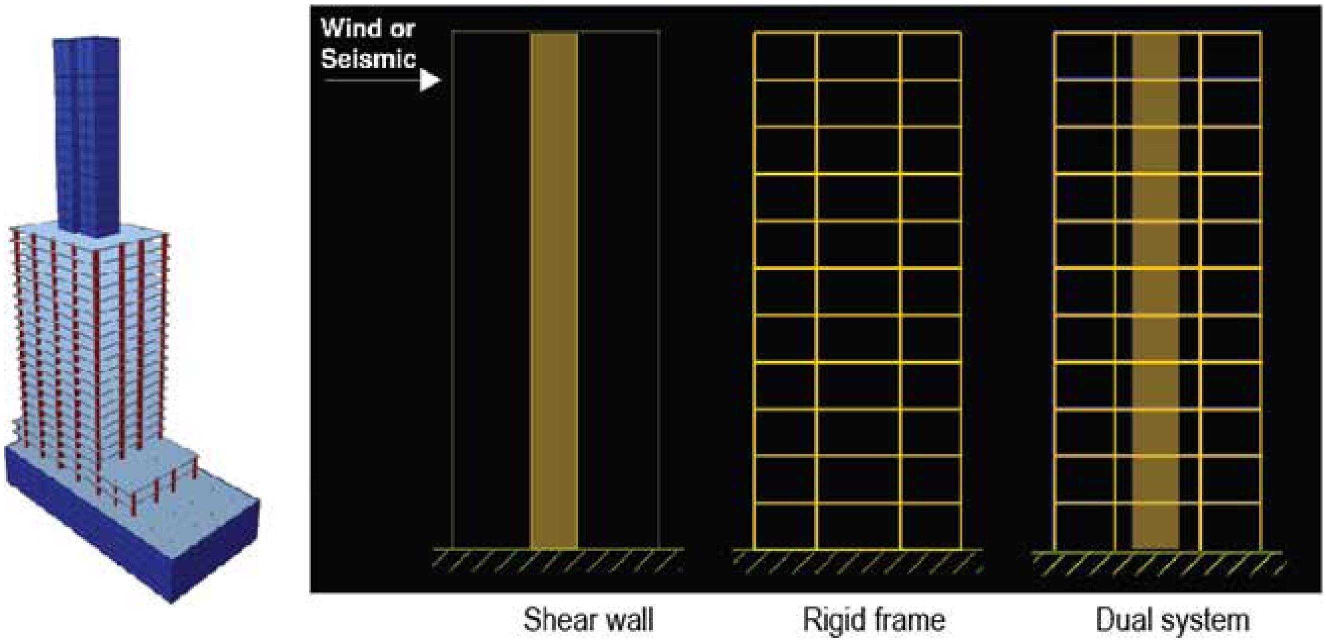


Fig. 2.11.1: Lateral systems for reinforced concrete buildings can comprise shear walls or rigid frames. A dual system comprises shear walls and a rigid frame. By code, the rigid frame must be able to resist at least 25% of the design forces. (Image courtesy of CKC Structural Engineers.)

Rigid-frame designs are excellent for larger-footprint structures such as parking structures or office buildings. Rigid-frame systems have constructability advantages when the floor system has a depth of 20 in. or more. Systems comprising long-span beams (refer to Fig. 2.6.20) or pan-slab construction can provide those depths efficiently. In pan-slab construction, the constructability of the frame design is maximized with little formwork expense when the beams and slab ribs have the same depth.

Upturned ductile beams at the perimeter of a parking structure are highly constructable and may also serve as barrier walls. Beam-column connections can be problematic, however, as reinforcement congestion is common (refer to Fig. 2.11.2). While congestion can be eased by

Fig. 2.11.2 Beam-column connections in rigid frames may present constructability challenges (photo courtesy of The Conco Companies).

widening the beam to match or exceed the column width, this solution may not be possible in high seismic regions. Strong-column/weak-beam systems will require extra attention to ensure paths exist for concrete flow and vibrator insertion. Such systems will also benefit from mixture designs that limit aggregate size to improve the flow of concrete between the reinforcement.

Shear wall solutions are economical and efficient. However, designers must take care to avoid increasing reinforcing bar density to levels that are not constructable, especially in boundary locations. Thickening the shear wall is the most economical congestion solution because it will ease bar installation without much added cost or loss of productivity. Also, note that reinforcing bar spacing must allow concrete flow. To ensure constructability, provide 3 in. square unobstructed vertical avenues for 2.5 in. vibrators, and provide 2 in. square unobstructed horizontal avenues for the installation of 2 in. diameter formwork tie rods on 4 ft centers in both directions. Consider shear wall configurations as shown in Fig. 2.11.3.

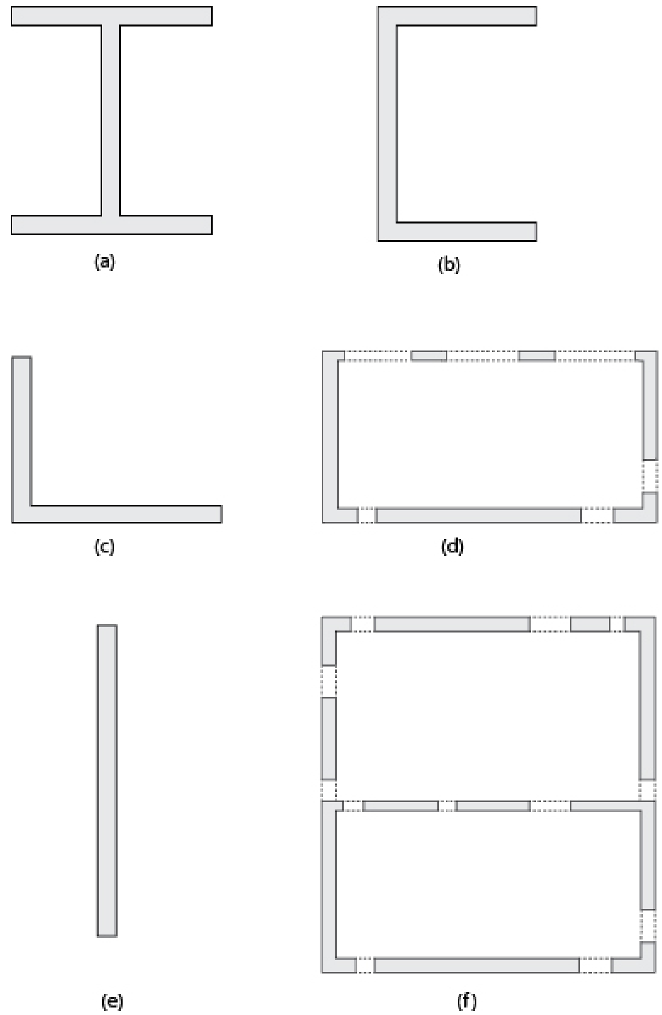


Fig. 2.11.3: Schematics of potential shear wall configurations: (a) barbell; (b) channel; (c) L; (d) barrel; (e) blade; and (f) double barrel.

The most productive walls are "blade" or straight shear walls without pilasters, and productivity decreases with every added corner. Locate the shear wall within the structure to capture as much gravity load as possible while keeping in mind possible crane locations and subsequent reach. As noted in the previous chapter (2.10), size each shear wall at the base of the structure. As loads reduce up the building, reduce reinforcement, then concrete strength, and then thickness. While possible, the least-productive modification is to shorten the length of the shear wall, as shortening a wall will require modification of the original wall form. If possible, establish the same length for all the shear walls in a structure. The thickness and reinforcement can vary. Maintaining a consistent length allows the contractor to use the same formwork repeatedly. Barbell-configured shear walls may be the most material-efficient, but they are the least productive for the contractor. If such a configuration is necessary, allow the inside vertical face to be drafted slightly wider at the wall face, which enables a one-piece wall form to be stripped without form disassembly. If barbell-configured shear walls are necessary, shape consistency between all shear walls is extremely important for maintaining productivity.

A centralized tube-core shear wall system is an excellent structural system as well as a productive solution for high-rise construction. Formwork systems have advanced to provide specialized solutions for these applications, including designs that accommodate the attachment of a concrete placing boom on the grillage that stabilizes the formwork (Fig. 2.9.5).

Constructability issues to consider during the design of tube cores include:

- Contractors will seek to optimize productivity by using self-climbing formwork systems to construct tube cores. As shown in Fig. 2.9.13, walls will typically be constructed a story or two ahead of the slabs, allowing the wall formwork to be clear of the deck construction operations. Self-climbing systems require vertically consistent anchor locations as they advance so that formwork designers will locate anchors away from wall openings. If possible, designers should design walls to have consistent opening locations and sizes at every floor, as designs with varying opening locations may cause the contractor to remove self-climbing systems from consideration.

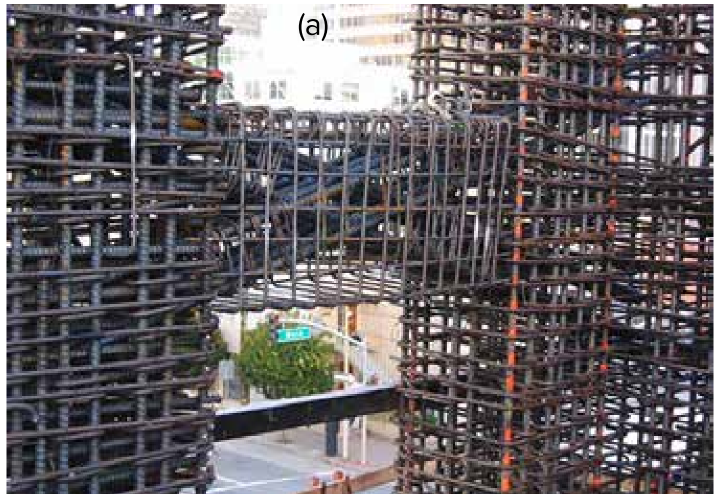
- Decks are connected to core walls using dowels and shear keys. Threaded couplers are a common option for the dowels, although many contractors prefer to use No. 5 reinforcing bars folded within the wall form during wall placement and subsequently bent out into the floor area prior to the slab placement. If the floor slab is post-tensioned, the PT anchors must be located just outside the face of the core wall (refer to Fig. 2.7.53). The PT cables must not be routed through or anchored within the walls, as this makes it impossible to optimize productivity by using self-climbing forms.

- Small cores (occupying less than 250 ft^2 horizontal area) create constructability challenges. Larger tubes are preferred, while tubes occupying more than 900 ft^2 of horizontal area should be designed as "double-barrel" tubes (refer to Fig. 2.11.3(f)). Consider the use of "L"-shaped shear walls to improve productivity for the construction of stairwells—stairwell tubes are small and unproductive.

- Forming and pouring a cast-in-place roof slab over the open shaft remaining after removing core wall formwork and work platforms is difficult and dangerous. Designers should, therefore, avoid designing the roof structure over a tube core as a cast-in-place slab. A productive and safe solution is to design the roof structure as a metal deck supported by structural steel beams connected to the walls using embedded anchor plates (Fig. 2.11.4).

Fig. 2.11.4: Construction of a roof over an open shaft. This roof will comprise composite steel beams with a concrete slab on metal deck. (Image courtesy of The Conco Companies.)

- Tube-core shear walls will have penetrations that require coupling beam details. While diagonally reinforced coupling beams are material-efficient, their combination of diagonal, horizontal, and vertical bars severely hinders productivity. Consider other options, including using steel fiber-reinforced coupling beams (Fig. 2.11.5). Tests have shown that steel fiber-reinforced coupling beams with beam span-depth ratios greater than 2.0 can achieve drift capacities of at least 5.0% and exhibit stable, flexural-dominated behavior when subjected to large displacement reversals (refer to **Evaluation of Seismic Behavior of Coupling Beams with Various Types of Steel Fiber Reinforced Concrete** .Such designs can eliminate the conflicts and congestion that are often created between diagonal bars and the adjacent boundary element reinforcement. The steel fiber-reinforced concrete increases the shear capacity in the coupling beam, which may also allow reductions in stirrup quantities and greater stirrup spacing. A paper published in the *CTBUH Journal* provides more information regarding coupling beams with steel fiber reinforcement: "**High-Rises, High Seismicity: New Materials and Design Approaches**."



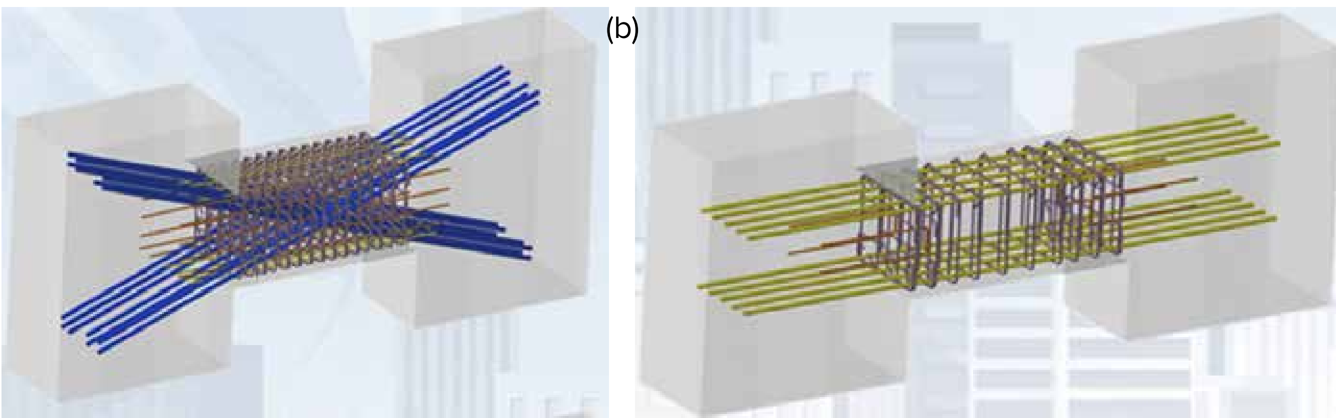


Fig. 2.11.5: Coupling beams at core wall penetrations: (a) construction photo of a diagonally reinforced coupling beam—the combination of diagonal, horizontal, and vertical bars severely hinders productivity; and (b) schematic illustrations contrasting a diagonally reinforced coupling beam (left) and a steel fiber-reinforced coupling beam (right). (Images courtesy of CKC Structural Engineers.)

2.12 FOUNDATIONS

Foundation design is localized due to soil conditions, but projects generally require mat footings, continuous footings, grade beams, caissons, pile caps, or mat slabs. In general, the most important constructability tip is repetition in size and reinforcement. For example, maintaining consistent sizes for footings, caissons, and pile caps will allow the contractor to efficiently lay out the foundation elements and reuse the formwork quickly. Further efficiency will be gained by maintaining consistent lengths and sizes of reinforcing bars. If changes are necessary, vary the reinforcement spacing, not the bar size. Also, be mindful of foundation tolerances. Earth-formed sides have tolerances of –1/2 in. and +6 in. Formed sides have tolerances of –1/2 in. and +2 in.

If the soil is adequately stable, the contractor will seek to "bank pour" without using formwork for footings and grade beams (refer to Fig. 2.12.1, 2.12.2, and 2.13.3). It is always an advantage if the bottom of all footings can be kept at the same elevation to expedite the excavation.

Be aware that the contractor will seek to use 18, 24, or 36 in. backhoe buckets for the excavation of continuous footings or grade beams. Because the reinforcement must have 3 in. cover, the reinforcement cage will be 6 in. narrower than the bucket size.

Fig. 2.12.1: Photo of excavation and reinforcement for an isolated spread footing with soil-formed sides. The concrete placement is commonly termed a "bank pour." (Image courtesy of Ceco Concrete Construction.)

Fig. 2.12.2: Photos of continuous footings that have been prepared for bank pours. (Image courtesy of Ceco Concrete Construction.)

To avoid the need to clear mud from a footing excavation after a rainstorm, many contractors will excavate only as much as can be placed during a single workday. While this is productive, it can lead to many construction joints in continuous footings and grade beams. Consider allowing stay-in-place form mesh at construction joints. This material allows reinforcement to pass through but contains the concrete. It also creates a roughened surface to transfer shear at the interface with the next concrete placement. For larger mat footings, the contractor may place an unreinforced, 3 to 4 in. thick, pumpable grout-based "mud slab" to protect the undisturbed soil from rain. The "mud slab" also provides a firm base for bolsters and standees

Fig. 2.12.3: Photo showing excavations, reinforcing bar mats, and column cages that have been prepared for a bank pour. Such footings may be called "spread," "mat," or "spot" footings in various markets. (Image courtesy of The Conco Companies.)

and can assist in the accurate positioning of the anchor bolt layout. When designing continuous footings or grade beams, minimize steps—a few 2 or 4 ft deep steps are preferred for constructability over more 6 to 12 in. deep steps.

Additional specific constructability quick tips include:

(a) When allowed by the building code, initiate concrete masonry unit (CMU) walls on a slab-on-ground rather than a separate continuous footing with CMU starter course(s). Allow the contractor to drill and epoxy the dowels for the CMU wall at the time of CMU installation (refer to Fig. 2.8.5 for a similar dowel application). For design guidance regarding slab thickening, refer to **UFC 3-320-06A**, "Concrete Floor Slabs on Grade Subjected to Heavy Loads."

(b) If foundation elements include anchor bolts (rods) (refer to Fig. 2.12.4), bolt groups should be centered in the footings, columns, or piers. The risk of placement errors can be minimized by specifying consistent layouts and bolt dimensions as well as equal bolt spacing in the x- and y-directions. Anchor bolt placement is challenging. Reinforcement congestion often prevents the placement of anchor bolts within tolerance, so minimizing reinforcement congestion can provide major benefits, even if it requires larger concrete sections. Also, note that various editions of the **AISC Steel Construction Manual** have long recommended oversized holes coupled with heavy plate washers for column base plates (refer to Table 2.12.1). **SPEC-117-10: Specification for Tolerances for Concrete Construction and Materials (117-10) and Commentary-Reapproved 2015** provides anchor bolt tolerances. Refer to the American Society of Concrete Contractors (ASCC) **Position Statement PS-14 Anchor Bolt Tolerances** for additional information. Lastly, encourage the determination of as-built anchor bolt locations as soon as possible after foundation placement. Timely communication of locations to the engineer of record and steel fabricator may allow slight alterations to be made in the base plates of steel connections.

Fig. 2.12.4: Anchor bolts are positioned in a foundation element using a reusable alignment template. (Image courtesy of The Conco Companies.)

Table 2.12.1: AISC Steel Construction Manual recommendations for hole sizes for column base plates

Bolt diameter, in.	Hole diameter, in.
3/4	1-5/16
7/8	1-9/16
1	1-13/16
1-1/4	2-1/16
1-1/2	2-5/16
1-3/4	2-3/4
2	3-1/4
2-1/2	3-3/4

(c) A structural slab-on-ground spanning between foundation elements is a common design solution for construction in brownfields and regions with soil swelling issues. When designing for constructability, keep in mind that such slabs must have enough strength to support the construction loads above, including the formwork load (10 lb/ft^2), construction live load (50 lb/ft^2), and dead load of the floor poured above.

When "mat" or "spot" footings are used, change the reinforcement spacing or depth before changing the footing size to reflect different loading. Whenever possible, maintain a consistent bottom elevation of the footings. If the spot footing width exceeds half the span distance to the adjacent spot footing, consider a continuous footing along the column line to maximize productivity (refer to Fig. 2.12.5). Formwork installation and reinforcing bar placement are more efficiently executed when constructing continuous footing than when constructing multiple "spot footings." Continuous footings also offer structural and soil-bearing advantages.

Fig. 2.12.5: An example of a lost opportunity to improve constructability by using spot footings in lieu of a continuous or mat footing. (Image courtesy of Ceco Concrete Construction.)

Also consider using a "mat slab" (refer to Fig. 2.12.6) in lieu of multiple spot footings. Mat slab construction is highly productive, as the necessary excavation and placement of the "mud slab" can be completed rapidly. Mat slabs can also use the highest-strength reinforcement available in the market, minimizing labor and congestion issues. Designers should check with local reinforcing bar suppliers to determine the grades (60, 80, or 100 ksi) in their inventories.

Fig. 2.12.6: A "mat slab" foundation. (Image courtesy of Related.)

As mat slab foundations become thicker, consider the implications of the heat of hydration in mass placements. Solutions that eliminate the need for internal cooling will enhance constructability. These solutions include allowing mixtures with high cement replacement levels and specifying design strengths at 56 days or more rather than 28 days.

Footings and brick ledges on sloped grades require steps (Fig. 2.12.7). To maximize constructability, use modular step dimensions of 2, 4, or 8 ft and standardize the step dimensions used on a project.

Foundation wall designs can be difficult to optimize for constructability, as they must reflect the site and building plan, degree of excavation, and supported structural framing. Repetition is key, but contractors recognize this is a challenging goal for the designer. Eliminating pilasters is a productive goal (refer to Section 2.6(g)). If pilasters cannot be avoided, use them on one side of the wall only, standardize the size, and allow (do not mandate) the vertical face of the pilaster side to be drafted slightly wider at the wall face to enable formwork to be removed without form disassembly for some gang-form applications.

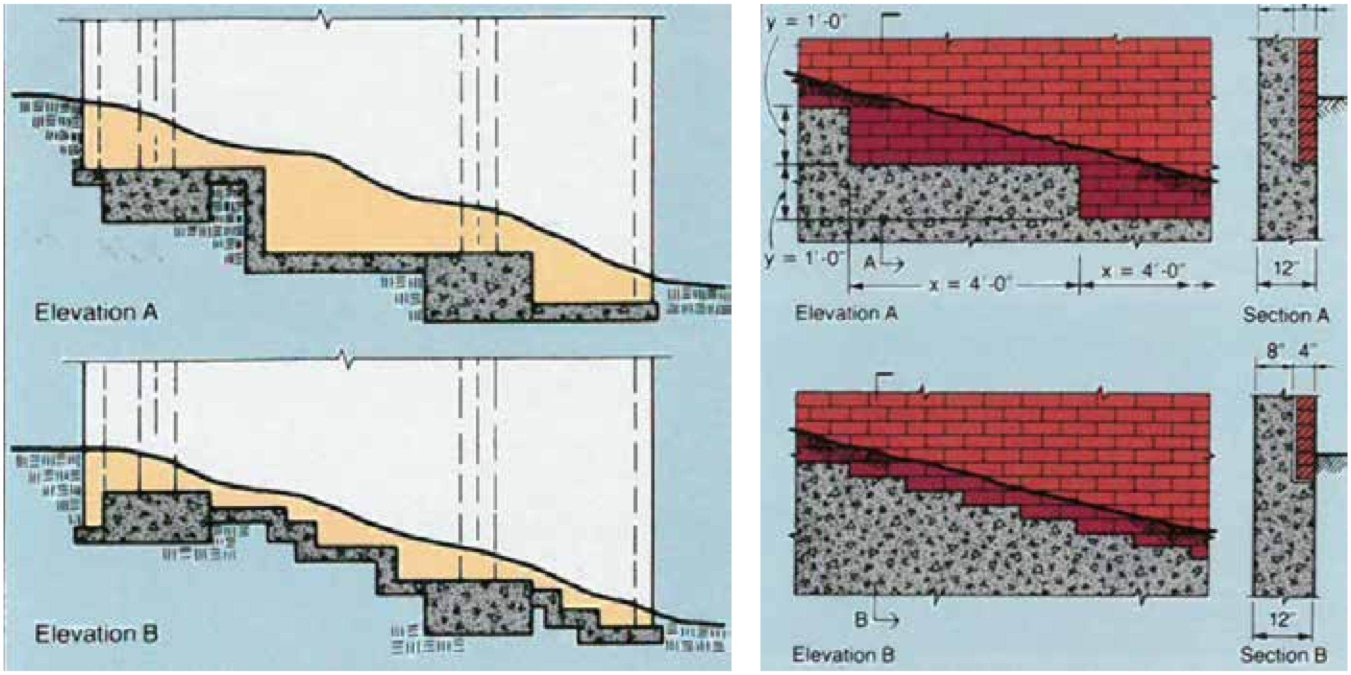


Fig. 2.12.7: Constructability of stepped footings (left) and brick ledges (right) will be enhanced by using fewer, larger steps (Elevation A) rather than many small steps (Elevation B). (Images courtesy of Ceco Concrete Construction.)

Contractors will seek to maximize the pour length of a foundation wall placement while the designer balances shrinkage needs. If possible, use crack, contraction, or control joints to minimize construction joints, as construction joints create constructability challenges (refer to Fig. 2.12.8). Measure for a needed construction joint from wall corners to help minimize locations. Therefore, only one construction joint may be needed if the distance between two corners is greater than the maximum distance and less than two times the maximum distance.

Ideally, foundation and structural walls constructed below grade can be formed with two-sided wall formwork. Consider widening the excavation/shoring footprint to allow room for workers, wall forms, and tie rods. A rule of thumb is to prove a minimum of 3 ft of workspace beyond the exterior wall face. If this workspace is not practical due to property lines or other constraints, foundation walls can be constructed using one-sided wall forms.

Fig. 2.12.8: Formwork for a construction joint in a foundation wall with two layers of reinforcement. This joint type is labor- and time-intensive because the horizontal bars must be continuous through the joint, and the form must be braced against high concrete pressures. (Image courtesy of Hensel Phelps.)

Foundation walls constructed using one-sided forms degrade productivity, as they require the contractor to anchor wall formwork ties to the retaining wall system (often sheet or H-piles and lagging) on the unformed side or use expensive formwork incorporating braces to transfer concrete pressure loads to a slab-on-ground (refer to Fig. 2.12.9). Often, one-sided wall formwork will require anchors to be drilled or welded to the excavation sheeting. Form tie rods are then connected to the anchors to absorb the form pressure. This is a labor-intensive process. Shotcrete is a viable alternative for one-sided foundation wall construction and should be allowed in contract documents (refer to Fig. 2.12.10) when reinforcement is sufficiently free of congestion for effective shotcrete placement. Using shotcrete placement in lieu of traditional formed concrete can enhance constructability by:

- Minimizing required labor-intensive one-sided wall formwork;
- Reducing tower crane reach requirements on projects with large bases (refer to Fig. 2.9.11);
- Minimizing the demand for crane time; and
- Improving the contractor's task sequencing (shortening the schedule)

Fig. 2.12.9: One-sided wall form with base anchors and adjustable braces required to withstand the pour pressure without formwork tie rods. (Image courtesy of Ceco Concrete Construction.)

Fig. 2.12.10: Shotcrete operations require no formwork or tie rods. (Image courtesy of The Conco Companies.) Reinforcing bar congestion hinders shotcrete's applicability, especially at pilasters. To improve constructability, upsize reinforcing steel and embed the pilaster into the wall as shown in Fig. 2.6.10 Plan A.

2.13 ON-SITE TESTING AND INSPECTION

With proper documentation and data control, modern testing technology enhances construction productivity. Historically, a testing agency is hired by the project owner to conduct construction quality assurance tests. On many projects, the testing agency is also hired by the contractor to improve the information flow needed to improve field delivery and quality control. Having a second testing agency to do comparative cylinder testing early in a project can often provide additional confidence in the reports and aid in solutions from test pours and mixture designs.

A competent, fully engaged, accredited testing agency can identify concerns early enough to avoid errors and associated rework. While the contractor is responsible for the work, a third-party lab can identify issues early to prevent problems downstream.

A competent, fully engaged, accredited testing agency can identify concerns early enough to avoid errors and associated rework. While the contractor is responsible for the work, a third-party lab can identify issues early to prevent problems downstream.

Testing and inspection are defined in the **2024 International Building Code (IBC), Chapter 17**; both continuous and periodic special inspections are defined. These independent and objective inspections are necessary for the project stakeholders and should not be minimized in scope or services. Insufficient inspections, delayed information, or inferior collection and analysis of data can greatly impede construction progress and cause unnecessary delays and conflict. Contractors seek fast, reliable inspection information to support and enhance productivity gains.

Common testing protocols include producing and crushing concrete test cylinders for strength verification as well as measuring concrete slump and air content. The modulus of elasticity (MOE) may also tested when specified. Incorporate ACI 301 in the project construction documents to avoid all-too-common inefficiencies, such as specifying excessively frequent testing. Section 1.7 of ACI 301 specifies random sampling of truckloads or batches of concrete, with at least one composite sample obtained for every consecutive 150 yd^3 of concrete or 5000 ft^2 of surface area of slabs or walls (Fig. 2.13.1). Call for increased frequency of testing only if required by the local building code or unusual conditions are encountered.

Fig. 2.13.1: Concrete tests include evaluations of air content. (Image courtesy of Flood Testing Laboratories, Inc.)

Specialized testing services include field inspections. Examples include inspection of reinforcement installation for compliance to design and installation tolerances, checking penetration resistance of grout, evaluation of shotcrete placement technique, shotcrete strength tests, checking PT tendon drape and elevations for compliance to design, evaluation of floor flatness and floor levelness, or F-min measurement (Fig. 2.13.2). Testing agencies need early involvement.

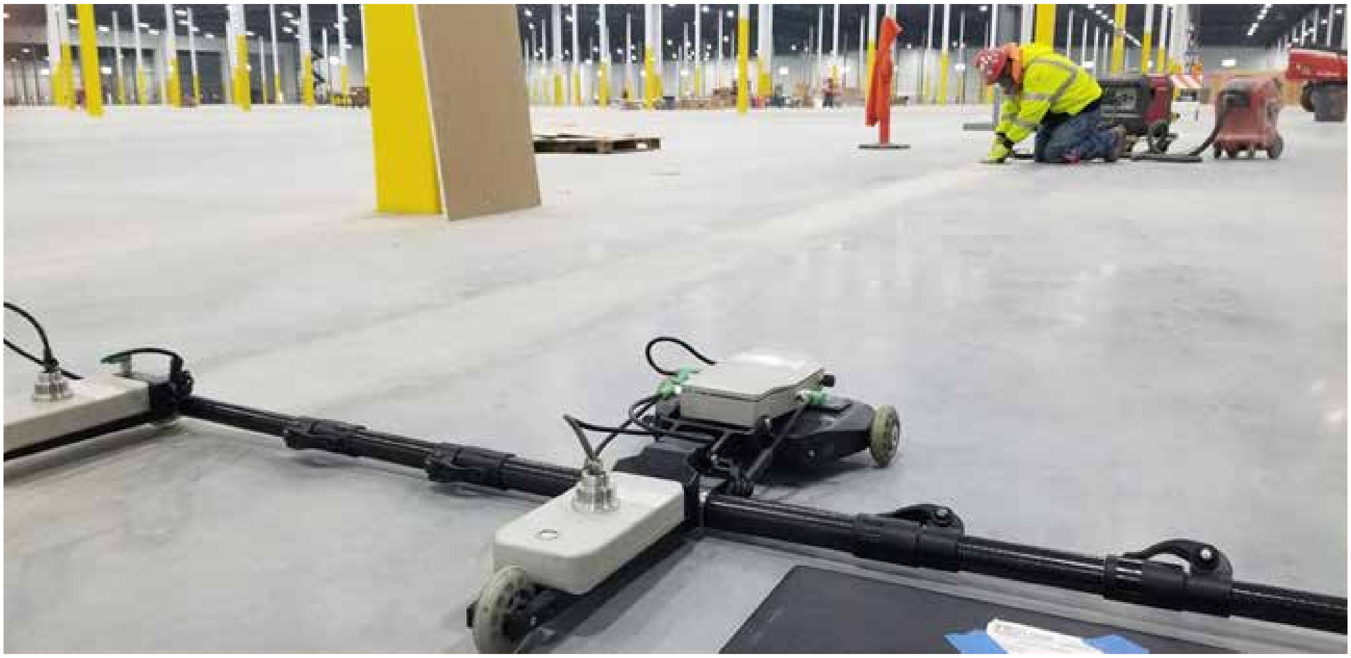


Fig. 2.13.2: A worker spot-grinds a floor slab to ensure it meets F-min tolerances. After grinding, the slab will be evaluated using the digital profileograph visible in the foreground. (Image courtesy of Flood Testing Laboratories, Inc.)

Accreditation of the testing agency shows that the firm is qualified to do the work. The American Association of State Highway and Transportation Officials (**AASHTO**) offers real-time accreditation status for verification. The U.S. Army Corps of Engineers (USACE) Materials Testing Center (MTC) validates commercial laboratories to perform materials testing services for the USACE. Look for ASTM C1077 accreditation for concrete testing on site and for ISO 17020 or ISO 17025 certification for field or laboratory technicians.

It is important to contact these agencies to verify accreditation and the scope of accreditation in advance of a project to avoid downstream issues. Often, testing agencies are contracted by inexperienced project stakeholders who are unaware of the productivity impact of an inferior provider. High-strength concrete (>7000 psi) testing capabilities, for example, are limited to fewer testing agencies. A project could come to a halt if an accredited agency is not available to conduct critical strength tests of column concrete.

Field technicians need certification as well. Certifying bodies such as **ACI Certification programs** and the International Code Council (ICC) have online, real-time verification of field technician certifications. Rather than doing so by the hiring body (owner or contractor), it is recommended that the project testing agency submits a list of the qualified technician(s) and their respective certifications during the preconstruction approval process for the requested testing scope. Lastly, note that some areas in the United States require additional local technician certifications. The key constructability tip is early engagement with an accredited testing agency.

Consider the following for success:

Fig. 2.13.3: A visit to the testing agency's lab should include an inspection of their test cylinder curing room. (Image courtesy of Flood Testing Laboratories, Inc.)

(a) Discuss and plan with the project testing agency before initiating site activity. Encourage a joint visit to the agency's facilities with the concrete contractor to help emphasize the importance of the agency's work and open communication channels (refer to Fig. 2.13.3). Testing high-strength concrete and ultra-high-strength concrete can be challenging, so use the site visit to verify the testing agency has adequate equipment and experience with such materials.

Include the testing agency during preconstruction meetings. Discuss areas of inspection concerns (for example, areas of reinforcement congestion), field sequencing plans and timing of field preplacement inspections, and inspection access that will support the project schedule. Count on your inspection agency to identify common and potential shortfalls or challenges during the preconstruction meetings. Also during these meetings, discuss documentation and data control, and empower the testing agency with current and complete design documents, including submittals. To maximize credibility, make sure stakeholders receive all results and reports.

(b) Know that the agency needs to dedicate time to staying current on design document updates and ensuring their efforts are in sync with the designer. Clarify for the testing agency whether the field reinforcement inspections should reference the structural drawings or reinforcement shop drawings. Using structural drawings often provides an added layer of shop drawing review of the designer's intent.

(c) Endorse direct communications between the inspection agency and the designer. Involve the reinforcement crew leader as well. Encourage immediate discussions when a field concern arises to expedite resolution while minimizing construction impact and inefficiency. Timely delivery of inspection information (data and observation) is critical to constructability. With today's cell phone coverage, inspectors can upload inspection information directly from the point of inspection to a reporting system. Use cloud-based shared documents that allow stakeholders to monitor the status of inspections in real time. Set expectations for the project by reporting this approach during preconstruction meetings.

Figure 2.13.4 provides an example of how sharing data can benefit the project team. The figure shows that 3-day strength test results rapidly declined from Test 1 to Test 3. The testing agency identified this trend and quickly communicated the low strength in Test No. 3 to the concrete producer. The concrete producer was able to immediately change the mixture, and the testing agency continued to collect data and communicate the results and trends in real time. These were important steps by the testing agency to support the concrete producer and contractor's scheduling and quality goals. Timely data also allow the stakeholders to identify the concrete placement location to assess the impact of lower strength and the potential strength gain of longer curing duration.

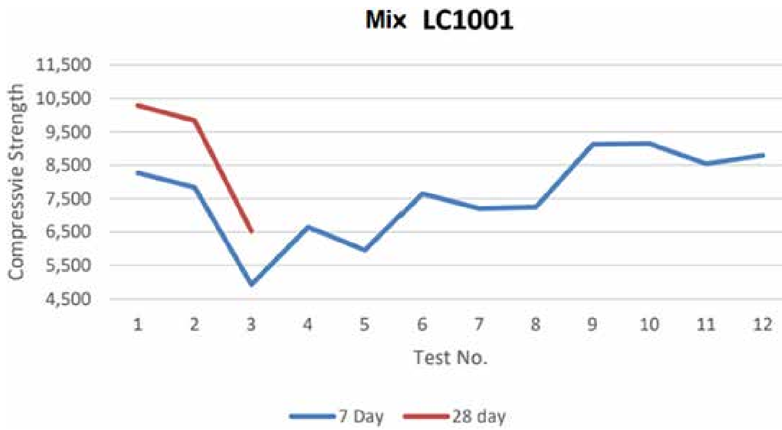


Fig. 2.13.4: Continual monitoring of 3-day test data can help avoid problems. (Image courtesy of Flood Testing Laboratories, Inc.)

Also, recognize that testing agencies are not infallible. Test technicians can make mistakes, such as producing poorly consolidated test cylinders (refer to Fig. 2.13.5). The relationships established during preconstruction meetings can help bring the stakeholders together to objectively target and quickly resolve such issues that would otherwise impact construction schedules. Once a problem has been identified, revisit as a team how to prevent recurrence.

Fig. 2.13.5: Proper consolidation of concrete in test cylinder molds is critical for obtaining reliable data: (a) Technicians rod concrete in cylinder molds; and (b) Improperly consolidated test cylinders will result in low strength test results. (Images courtesy of Flood Testing Laboratories, Inc.)

Lastly, be aware that standards for acceptance criteria are based on statistical concepts that permit a low test, and it is standard practice for concrete producers to design concrete mixtures based on a probability of approximately 10% that an individual strength test may be less than specified. For more on this topic, refer to the article "**Expect Compressive Strength Test Results Less Than Specified Strength on Every Project**."

(d) Support the application of modern technology to achieve constructability. Maturity sensors, for example, offer contractors the ability to optimize a project schedule by verifying strength gain in real time and using the data to safely accelerate form release or tensioning of PT cables. Testing agencies can help calibrate the sensor results by producing data on strength development as a function of time for similar mixtures to those used in the field (refer to Fig. 2.13.6). The designer can support the application of this technology by referencing ACI 301 in the project construction documents and specifying the maturity method in accordance with ASTM C1074 (**Standard Practice for Estimating Concrete Strength by the Maturity Method**) as an alternative method for evaluating in-place concrete strength for formwork removal, cessation of curing, or stressing of post-tensioning.

Clearly, lab-cured cylinders do not represent the concrete in place, as ASTM C31/C31M (**Standard Practice for Making and Curing Concrete Test Specimens in the Field**) requires test specimens to be maintained at 100% humidity and a constant temperature after transport to the lab. However, using field-cured cylinders to determine the timing of stripping and stressing operations is inefficient, often results in delays, and impacts the project schedule. Specify field-cured cylinders only for special situations, such as a particularly cold weather placement.

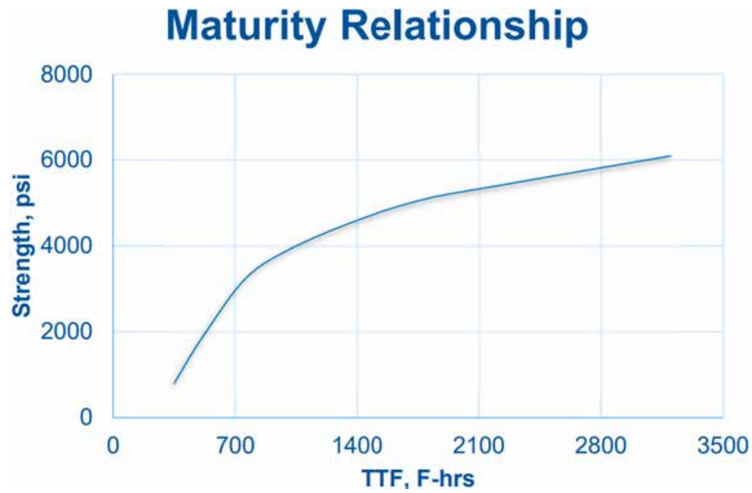


Fig. 2.13.6: The testing agency develops the relationship between compressive strength and temperature-time factor (TTF) for a concrete mixture similar to those that will be evaluated on the project. (Image courtesy of Flood Testing Laboratories, Inc.)

(e) Avoid requiring inspections of certified batch plants. This is unnecessary unless a project requires a unique special mixture or large placement. Require the plant's national ready mixed certification information to be provided during submittals.

(f) Do not require alkali-silica reaction (ASR) testing when local aggregates have no history of reactivity. Such testing is aggressive and often limits acceptable aggregates. Also, note that it is unnecessary to test on site for chloride on all placements.

(g) Very few Cement and Concrete Reference Laboratory (CCRL)-certified labs in the United States are available for ASTM C469/C469M. Before specifying specific MOE concrete, consider testing agency availability. Higher-compressive-strength concrete may be needed to achieve higher MOE design goals. Acceptance testing for the MOE is based upon an average of placements. A low MOE on a placement is not "nonconformance." Monitor MOE data as they become available. The designer may elect and find it necessary to make design adjustments to structural elements based on the achievable MOE of the mixture aggregates.

(h) Testing at the point of placement (refer to Fig. 2.13.7) can be used to determine losses in slump associated

Fig. 2.13.7: A technician conducts a slump test on a formwork deck near the point of placement. (Image courtesy of Ceco Concrete Construction.)

with concrete pumping. However, after slump loss has been established through early testing, further testing should be conducted at the truck until the conveyance distance has changed significantly (for example, after the conveyance height has increased by 10 floors). Continued point-of-placement testing is dangerous and unproductive in many placement locations. It is particularly important to test air content at the truck, as tests conducted on fresh concrete after pumping will not correlate with the air content and durability of the hardened concrete. In brief, concrete should not be rejected based on air tests conducted after pumping. For more information on this topic, refer to this video by Tyler Ley: **Why do you lose air volume when pumping air entrained concrete and why does the air come back?**

An engaged accredited testing agency should be a valued project teammate that can provide key information, if transmitted efficiently, to ensure constructability goals are achieved. Leverage their expertise early and often to enhance a project's constructability.

2.14 SPECIFICATIONS FOR CONSTRUCTABLE CONCRETE

Project specifications set acceptable designer standards for a project's materials, means, and methods. Improving the constructability of concrete production and construction can be achieved by considering a few fundamentals and best practices when developing project-specific specifications.

Figure 2.14.1 is a popular illustration of a divergence between design theory and actual practice. All too often, there is an analogous delta between construction theory and actual practice. Actual practice should be considered when drafting project specifications, as specifications should reflect the purpose of the concrete elements, the local availability of materials, the schemes of construction, and the needs of the project stakeholders (refer to Fig. 2.14.2).

Fig. 2.14.1: A literal divergence between design and practice.

During specification development, designers must be keenly aware that their decisions can greatly impact the productivity of the contractor and concrete producer.

Fig. 2.14.2: Concrete specifications serve multiple project stakeholders with differing roles, needs, and perspectives. (Image courtesy of Kiewit Corporation.)

Typical concrete specifications contain the following content and expectations:

References: It is important that cited references are clear and specific in scope, as they become part of the specification. ACI has developed several specifications that are often referenced by designers in project contract documents. The most familiar of these referenced specifications are **ACI 117-10**, "Specification for Tolerances for Concrete Construction and Materials and Commentary," and **ACI 301-20**, "Specifications for Concrete Construction." While specifiers often cite these ACI documents, it is important for specifiers to comply with the Mandatory Requirements Checklist in the Notes to Specifier provided with each reference specification. The Mandatory Requirements Checklist identifies provisions that do not have default requirements. For these provisions, specific requirements must be provided in the contract documents. If not provided, much of the reference ACI document is not applicable to the construction of the project. **ASCC Position Statement #42** provides additional information. The checklist provides, amongst others:

- Designated areas to be treated as architectural concrete;
- Designated portions of the structure to be constructed of lightweight concrete;
- Designated portions of the structure to be treated as mass concrete;
- Designated portions of the structure to be constructed as industrial floor slabs;
- Exposure class (resistance to sulfate, freezing and thawing, low permeability, corrosion protection) for portions of the structure; and
- Designated portions of the structure with corresponding specified concrete compressive strength.

An Optional Requirements Checklist is also provided with each ACI reference specification. This checklist identifies Specifier alternatives or additions in the reference specification as well as the action required or available to the Specifier. The Specifier should review each item in the checklist and adjust according to the needs of a particular project by including those selected alternatives or additions.

Again, the ACI specifications are referenced in project specifications. ACI 301, for example, should be referenced using a statement such as:

> "Work on (Project Title) shall conform to all requirements of ACI 301-20, "Specifications for Concrete Construction," published by the American Concrete Institute, Farmington Hills, Michigan, except as modified by these Contract Documents."

Specifiers must not copy individual sections, parts, articles, or paragraphs from ACI 117 or ACI 301 into the project specification because taking them out of context may change their meaning.

Further, if sections or parts of the reference specifications are copied into the project specification or any other document, it is not appropriate to refer to these sections or parts as ACI specifications.

Qualification and testing of materials: It is extremely important that the designer identifies and qualifies the locally available materials before specifying their use. Oftentimes, materials require months or years to be qualified for use, especially when used on infrastructure projects or projects in aggressive environments that require service life modeling or long-term serviceability analysis. These qualifications should be established before the contract documents are complete, or the contractor may not find the materials needed by the specifications. If specifications do not reflect local materials, mixture designs, or the contractor's building scheme, contractor pricing will be elevated, and it may be impossible to proceed with construction.

Submittals: Requirements for submittals provide the owner and designer with an opportunity to learn and approve the contractor's plans for materials, mixture designs, work plans, curing plans, quality assurance, and quality control plans. These are managed through the submittal requirements (refer to the article "**Purpose and Pitfalls of Submittals and Shop Drawings**").

Materials: Materials are often prescribed in a fashion that is a challenge for constructability. Examples include specifications calling for materials and respective properties that are not locally available. Contractors often have insufficient time during the bidding process to source materials as prescribed, so they assume such materials have been verified to be available when specified. A common error is reissuing an old, previously used specification that prescribes materials that no longer exist or are not relevant to current construction technology.

Batching and delivery of concrete: Specifiers should understand the construction scheme or local batching capabilities. If the batching and delivery parameters are inadequately specified, constructability will be greatly impacted.

Concrete mixture design: The following section of this chapter discusses the comparison of prescriptive versus performance mixture design specifications. To maximize constructability potential performance, concrete mixture design specifications are encouraged. If a concrete mixture design specification must be prescriptive, the following constructability principles can be considered. Each mixture design property should be balanced and reviewed for constructability. Over-specifying properties can be problematic, expensive, and unproductive. Use care when reviewing the following properties to ensure relevance to each project:

1. Strength and MOE: Consider the strength requirements for construction and the structural element service life design. To pursue higher strengths, lower the water-cement ratio (*w*/*c*), supplement with admixtures, and lower fly ash content. To pursue higher MOE, higher-compressive-strength concrete may be needed to achieve higher MOE goals. MOE is largely controlled by the coarse aggregate. Identify "stiff" coarse aggregate, verify it is available locally, and qualify it with testing. The designer may elect and find it necessary to make design adjustments to structural elements based on the achievable MOE of available mixture aggregates.

2. Durability: Identify if resistance to freezing and thawing, sulfate resistance, permeability, or service life are appropriate mixture design variables for the project application. If additional durability needs are not warranted, resist including the admixtures.

3. Workability: A key to concrete material constructability is the workability of the mixture. Consider slump retention, consolidation, and finishing demands in the mixture design. If

self-consolidating concrete (SCC) is necessary, improve aggregate grading, balance paste and mortar, and enhance with admixtures.

4. Economics: Especially with prescriptive specifications, consider the mixture cost, field operations, and the quality of the mixture. Ready mixed concrete producers will provide the material as specified and charge accordingly. Over-specifying special mixture properties will result in unnecessary added costs to the project owner.

5. Thermal effects: When applicable, consider maximum concrete hydration temperatures and temperature differentials in the placed element. Manage these values through the mixture design, including lowering the total cementitious material, increasing the quantity of fly ash, using better-quality aggregates, and specifying concrete strength at the age of 56 days rather than 28 days for the elements of concern. While mixture design is critical in the management of thermal performance, additional measures should be considered, including blankets and internal cooling techniques.

Handling, placing, and constructing: Proper specification is important for long-term service life and needs to be consistent with the concrete's purpose. For example, if shrinkage is a concern, specify increased aggregate size and reduced w/c and allow workability to be enhanced using admixtures. For additional requirements, refer to the Mandatory Requirements Checklist and the Optional Requirements Checklists associated with Section 5 of ACI 301.

Quality assurance and quality control of work implementation: Project specifications must reflect the contracting delivery model, as roles and responsibilities will vary depending on the contracting method. Achieving the desired quality starts with the submittal requirements. Are testing or mockups needed? And to what extent will mockups qualify the concrete and process? These needs must be defined by the designer in conjunction with the owner. What inspection and testing plans (ITP) are needed? What field verifications are necessary? What are the specific and objective measures of inspections and testing? Shall the concrete mixture's pumpability, workability, finishability, and curing plan be trial-tested? Mockups should include actual remedial processes that reflect the contractor's intentions or other subjective concerns like color and texture.

Acceptance: Well-defined and specific acceptance criteria are important to prevent a source of conflict from subjective acceptance.

The gap between concrete operations and an inadequate or misleading concrete specification can create unintended conflicts. Materials need to match the construction operation, and the construction operation needs to match the materials. It can be said that concrete that meets the specifications, facilitates the construction field operations, and reduces rework is "fit for purpose." The photos in Fig. 2.14.3 illustrate a variety of construction operations where the concrete specifications, if they do not match the construction operation, can impact constructability. While these may be extreme situations, they highlight the need for a concrete specification to match the construction operation.

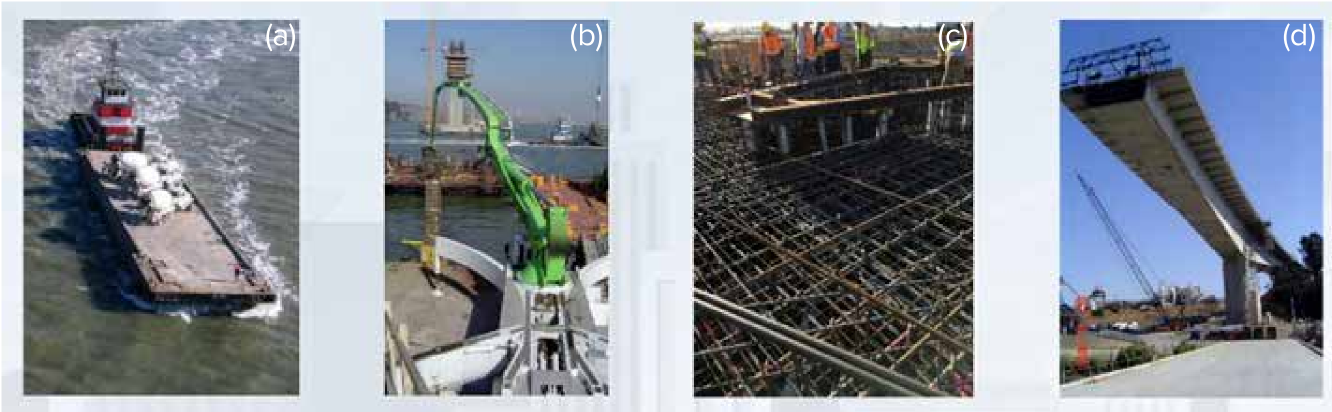


Fig. 2.14.3: Complex construction operations require compatible specifications: (a) concrete batches that will be transported by barge will require extended working times; (b) underwater concrete placements will require concrete mixtures with anti-washout properties; (c) large foundation elements will require concrete mixtures with low heat of hydration and are suitable for acceptance based on concrete strength at 56 days; and (d) segmented precast concrete for bridges will require formwork and mixtures that satisfy aesthetic demands and durability requirements. (Images courtesy of Kiewit Corporation.)

Specific tips for improving specifications for constructable concrete include:

(a) Avoid common concrete specification flaws, such as failing to specify requirements or defining requirements that are:

- Conflicting or irrelevant;
- Unnecessary and prescriptive;
- Overly conservative; or
- Unrealistic.

(b) Improve specifications for construction by using specific, measurable, achievable, relevant, time-bound (SMART) goals as part of the review process to ensure the specifications are constructable.

(c) Be aware of the conflicting demands of prescriptive specifications versus performance specifications. A prescriptive approach imposes a requirement that may not relate to performance, relies on others' knowledge about how a material will perform, and may not correlate with the methods used to complete the work. A performance specification is a process of carrying out an action that requires successful verification of the action. Verification methods must be well-defined and standardized to guarantee performance, allowing the contractor to marry the construction concept to the material performance. Designers must avoid placing a prescriptive requirement upon a performance approach, as this creates conflicts and poor constructability results. A guide published by the National Ready Mixed Concrete Association (NRMCA), **"Specifying Sustainable Concrete,"** provides excellent recommendations for specifiers. The guide includes a table listing the negative impacts of prescriptive specifications on sustainability, performance, and cost. Further, it recommends performance specifications because they allow the concrete producer to define the mixture proportions while also holding the producer responsible for meeting the performance criteria. Performance specifications encourage concrete producers to improve product quality by stimulating innovation, reducing construction costs, minimizing construction time, and minimizing environmental footprint.

(d) Project implementation has common challenges with materials and mixtures. It is important to understand the local conditions, market challenges, material availability, material quantity limitation, and properties of the local materials. Have the local materials been tested for performance? If not, is there time to do so before construction starts (refer to Fig. 2.14.4)? These variables will impact how a project is built and affect its constructability. Specifications need to reflect these variables, especially on larger projects.

(e) Tremie concrete (also termed drop-chute concrete) in drilled shafts requires unique properties. A key property is the ability to naturally flow under the influence of gravity while remaining stable and exhibiting no segregation (refer to Fig. 2.14.5). Refer to Chapter 2.8 and the *Concrete International* article "**Free Fall of Concrete**" to evaluate if specifying tremie use is necessary, or an unnecessary and unproductive cost.

(f) Concrete for pumping long distances through slick lines requires a fluid mixture to minimize line friction.

(g) Specifications for mass concrete applications should be developed with a focus on ensuring low heat of hydration, minimal shrinkage, long-term strength, and high

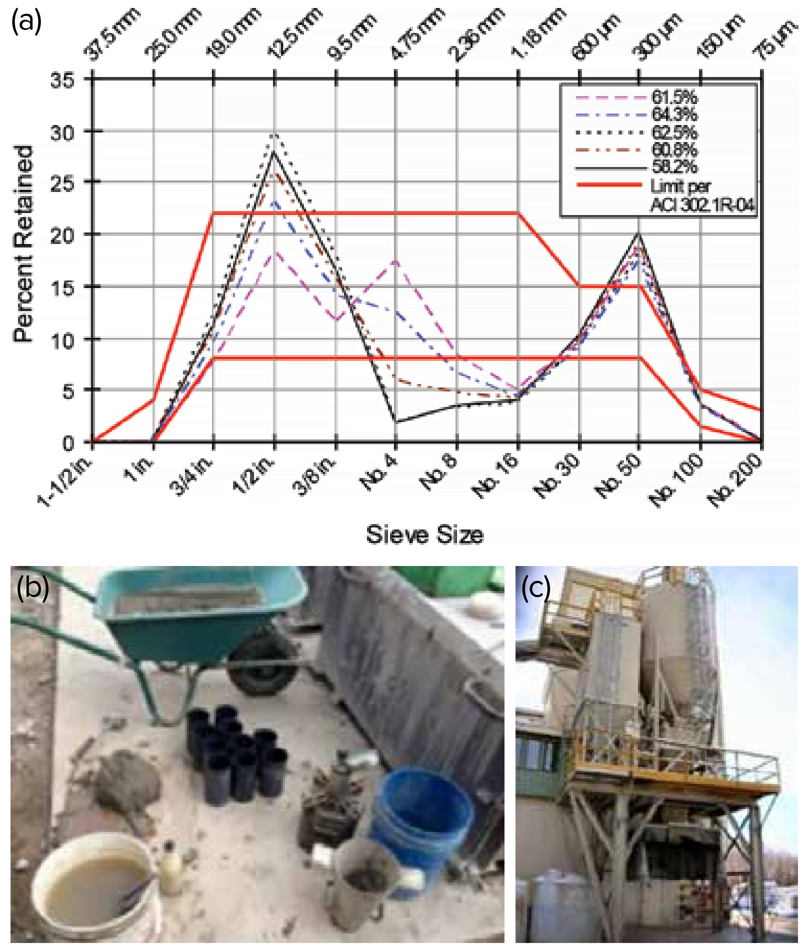


Fig. 2.14.4: Development and testing of concrete mixtures can take several weeks: (a) developing the basic proportions ("Bookcrete") can take 30 to 60 days; (b) evaluating and refining the mixtures in the laboratory ("Labcrete") can take 90 to 120 days; and (c) further refinement at scale ("Concrete") can take 15 to 30 days of intense work, and optimizing mixtures may take several iterations of this process. (Images courtesy of Kiewit Corporation.)

Fig. 2.14.5: Tremie concrete requires mixtures capable of flowing without segregation: (a) example of "bad" concrete mixture approved by client; and (b) examples of "good" concrete mixtures proposed by contractor. (Images courtesy of Kiewit Corporation)

MOE. Because mass concrete placements may provide limited access for vibration, they may be considered good applications for SCC. Meeting all listed requirements is a difficult balance and often requires multiple iterations of design of mixtures, producing mockups, and testing (refer to Fig. 2.14.6).

Fig. 2.14.6: Mass concrete placements typically require extensive testing programs, including: (a) instrumentation of large mockups to evaluate heat build-up; and (b) development of SCC mixtures. (Images courtesy of Kiewit Corporation.)

(h) Designers should consult with local producers to determine available options for establishing a time limit to the end of discharge of ready mixed concrete, as selection of a time limit should include consideration of "ambient conditions, types of cementitious materials and admixtures used, placement procedures, and projected transportation time between the batch plant and the point of delivery" (refer to **ASTM C94/C94M, Standard Specification for Ready-Mixed Concrete**). The practice of placing a 1-1/2-hour limit on delivery times creates major challenges for concrete construction in urban areas. Batch plant locations are typically far from areas of development growth, and traffic congestion and associated delays can be unavoidable. The time limitation has, therefore, resulted in lost productivity and increased costs for contractors and concrete suppliers, and it has needlessly increased the carbon footprint of the construction industry at large. Modern production processes and materials allow suppliers to deliver batches capable of extended working times and meeting constructional and structural requirements.

Allowing the use of high-range water-reducing admixtures (HRWRAs) to compensate for slump loss, for example, will ensure that the contractor receives concrete with the workability needed for proper placement and consolidation as well as the required strength.

In summary, the keys to developing specifications for constructable concrete include:

- Ensure the specification is relative to the work and needed purpose of the element.
- Make the specification clear, concise, and specific.
- Align the specification with available local materials and supplier capabilities.
- Ensure the specification is achievable and executable by the construction process.
- When possible, make the specifications performance-driven.
- Allow for some flexibility for the material producer and contractor for innovation.
- Ensure the material and application are technically sound and verifiable.

2.15 COORDINATION AND COMPLETION OF DRAWINGS

Poorly coordinated and/or incomplete design drawings result in inaccurate bids, and they force contractors to complete the needed coordination and design through multiple requests for information (RFIs). The disjointed process leads to delays, added costs, change orders, and a general dissatisfaction with the completed project.

A set of documents that is complete and coordinated before construction is essential for achieving productivity. In 2023, FMI Corporation released a labor productivity study. According to the FMI poll, “4 of 5 Contractors said low-quality design/construction documents (plans and specs) are a top external factor stunting productivity” (**2023 FMI Labor Productivity Study**).

While design team members use their education and experience to translate architectural concepts into a constructable format, construction team members use their knowledge and experience to construct the project with a focus on cost and schedule. The design process may include the evaluation of a variety of concepts and solutions. The construction process typically seeks maximum productivity. Changes during construction caused by incomplete and/or poorly coordinated documents are not good for a contractor’s productivity.

In 2020, the American Society of Concrete Contractors (ASCC) conducted a Constructability Survey. Their survey indicated that the number one barrier to constructability was a lack of completeness of drawings, with the coordination of drawings second and the coordination of drawings and specifications third. Concrete embedded items from specialty structural engineers (for example, cladding) need to be provided and coordinated by the structural engineer of record (SER), even though those details are often provided during the concrete construction phase. Beware of standard details. Standard details can be added to the drawings without much thought and often conflict with the designers’ intent or other project-specific details. This can lead to ambiguity, conflicts, and change orders.

Designers face many pressures during the design process, and these can result in negative impacts on the constructability of the construction documents. These pressures include:

- Increased competition;
- Lower design fees;
- Accelerated design schedules;
- Increased architectural design complexity;
- Owner decision delays and changes;
- Delegation of responsibilities for design and coordination;
- Accelerated project delivery;
- Inability to retrain experienced staff and train the less experienced; and
- Increased reliance on design technology.

To address these concerns, many organizations have published requirements and guides. The following sections summarize key sources of information from the Council of American Structural Engineers (CASE), Construction Specifications Institute (CSI), American Society of Civil Engineers (ASCE), International Code Council (ICC), American Concrete Institute (ACI), American Society of Concrete Contractors (ASCC), and ASTM International.

Council of American Structural Engineers

- **CASE 962-D**, "A Guideline Addressing Coordination and Completeness of Structural Construction Documents," first published in 2003 and updated in 2020;
- **CASE Tool 9-1**, "A Guideline Addressing Coordination and Completeness of Structural Construction;" and
- **CASE Tool 9-2**, "Quality Assurance Plan."

The guidelines discuss the important aspects of design relationships, communication, coordination and completeness, guidance for dimensioning of structural drawings, and the effects of various project delivery systems and document revisions. It closes with recommendations for the development and application of quality management procedures, internally within the design firm and externally between disciplines. After the preparation of organized and clear calculations, the drawings must be coordinated with the calculations, the specifications must be coordinated with the structural drawings and calculations, and the "general notes" must be coordinated with the specifications. Examples of coordination with other disciplines include:

- Dimensions;
- Tolerances within the structure and between structure and finishes (**ACI 117.1R-14** and **ASCC Position Statement #6**);
- Geotechnical requirements;
- Mechanical/electrical requirements; and
- Requirements of specialty structural engineers.

CASE 962-D is focused on coordination with architectural drawings. "The Structural Engineer of Record (SER) should check that tolerances for structural materials are accommodated. Construction materials will always deviate from the 'ideal' conditions shown in the drawings due to a variety of factors such as fabricating and erection practices, material properties, or quality of workmanship. Therefore, it is critical for the SER to review the structural design in consideration of industry tolerances. The SER should prepare the design with specifications to allow integration of other building systems, keeping in mind the structural system's tolerance requirements. More specifically, the design and design details of prefabricated wall panels, partitions, fenestrations, floor-to-ceiling door frames, and similar elements must account for clearance and adjustability regarding the tolerance envelope of the structural framing."

CASE 962-D also states that construction documents that are well-coordinated within themselves and with the other project disciplines will provide sufficient information for bids or cost estimates to accurately predict cost and schedule, efficiently produce shop drawings, and allow the contractor to build the structure as the SER intended. In general, complete structural documents will:

- Include clear descriptions of structural elements and their material specifications;
- Be coordinated within and externally with other project disciplines;
- Show all dimensions necessary for construction and the relationship of structural components to nonstructural elements;
- Document the codes and loads used for design;
- Identify and provide requirements for portions designed by specialty structural engineers; and

Specify the quality assurance requirements. A key to achieving the desired level of document quality throughout the profession is for each structural engineering firm to focus on and develop its own specific quality management plan and to implement that plan on each project. **CASE 962-D** includes a list of the consequences of uncoordinated and incomplete documents:

- Inaccurate project estimates and missed budgets;
- Construction misunderstandings;
- Increased number of RFIs and change orders;
- Conflicts between design and construction teams;
- Disappointed and angry owners; and
- Potentially costly and demoralizing litigation.

The document also contains a Drawing Review Checklist to support the SER-specific quality management plan. The checklist includes sections devoted to the coordination of structural drawings with architectural, civil, and MEP drawings. It also includes sections devoted to specific system types. The following bullet points reflect many of the items in the checklist for concrete systems:

- Do contract documents reference applicable ACI and Concrete Reinforcing Steel Institute (CRSI) standards, including ACI 301, 117, 318, and the CRSI "Manual of Standard Practice"?
- Are all structural elements clearly identified, located, dimensioned, and detailed to show:
    - Locations?
    - Sizes and orientations?
    - Grade and size of each type of reinforcement for each member type?
    - Details of ties, spirals, or stirrups for each member type?
    - Splice locations, types, and details?
    - Bar cover requirements for each member type?
- Are sections and details complete, and are they referenced?
- Are typical details adequately referenced and applicable?
- Have typical details been evaluated per applicable schedules and references?
- Have possible reinforcement congestion problems been evaluated?
- Are minimum reinforcement requirements met?
- Are sleeve locations shown and detailed?
- Is trim reinforcement identified around sleeves or openings?
- Are details provided for construction joints?
- Are slab depressions noted and detailed?
- Are finishing and flatness requirements specified?
- Are camber requirements identified?
- For post-tensioned (PT) concrete, do the construction documents define:
    - Minimum compressive strength at the time of post-tensioning?
    - Prestressing force magnitudes and locations?
    - Effective force requirements for uniform and banded tendons?

Construction Specifications Institute

The Construction Specifications Institute (CSI) created the "**Project Delivery Practice Guide**." The guide recommends design team coordination with sufficient time dedicated to performing coordination tasks. It states that a well-planned, well-executed, and well-enforced coordination program can result in fewer addenda items, fewer requests for interpretation, fewer change orders, fewer disputes, and reduced project costs. Ideally, the documents for construction prepared by the architect and the other design team members will be as consistent as if they were prepared and produced by one source. The guide notes that incomplete coordination results in:

- Duplications;
- Omissions;
- Discrepancies; and
- Terminology differences.

American Society of Civil Engineers

The American Society of Civil Engineers (ASCE) published a discussion of designer, contractor, and owner responsibilities in ***Quality in the Constructed Project: A Guide for Owners, Designers, and Constructors***.

International Code Council

Chapter 16 Structural Design, of the 2024 International Building Code (**2024 IBC**) states:

1603.1 General
Construction documents shall show the material, size, section and relative locations of structural members with floor levels, column centers and offset dimensions. The design loads and other information is pertinent to the structural design…shall be indicated on the construction documents.

American Concrete Institute

As previously noted in this document, pertinent American Concrete Institute (ACI) standards include the following documents:

- **ACI 301-20**, "Specification for Concrete Construction"
- **ACI 318-19**, "Building Code Requirements for Structural Concrete and Commentary"
- **ACI 117-10**, "Specifications for Tolerances for Concrete Construction and Materials and Commentary"
- **ACI 117.1R-14**, "Guide for Tolerance Compatibility in Concrete Construction"

ACI 318-19 Chapter 26 confirms the statement from IBC Section 1603.1 by establishing the minimum requirement for information that must be included in the construction documents. Section 26.1.1 addresses items the design professional shall specify in the construction documents, if applicable. These include:

- Design information. The information shall be project-specific and developed during the structural design. It describes the basis of the design or provides information regarding the construction of the work;
- Compliance requirements. The compliance requirements are general provisions that provide a minimum acceptable level of quality for the construction of the work. It is not the intent of the Code to require the licensed design professional to incorporate, verbatim, the compliance requirement into the construction documents; and

- Inspection requirements. Section 26.13 provides inspection requirements to be used in the absence of general building code inspection provisions. These inspection requirements are intended to verify that the work complies with the construction documents.

Examples of design information that should be communicated include:

- The sequence of placing reinforcing bars in conjunction with strands (necessary to ensure reinforcement locations are as intended);
- The timing of backfilling of foundation walls (necessary to ensure satisfactory strength and deflection of walls designed as retaining walls and/or walls supported by floors);
- Design load information (necessary to ensure capacity is not exceeded by construction loads). Load mapping, showing specific locations of design loads and applicable live load reductions, is the preferred method of design intent clarity; and
- Movements during construction and over time (necessary for the design of connection details and to ensure the contractor, architect, and owner are aware of anticipated movements due to prestressing, dead and live loads, and temperature changes).
  - Note that the designer must also provide dead load deflections for structural steel floors with slabs on a metal deck, as the contractor needs this information to determine the additional concrete required in the slab to achieve levelness.

On the latter point, Table 2.15.1 provides an example of calculated movements for an actual project. Although not noted in this example, foundation movements and vertical member compression become important factors as a project becomes higher. By providing analytical predictions of such movements, the designer can encourage the contractor to anticipate and modify casting to accommodate such. For further reading, a discussion of the effect of post-tensioning is provided in the article "**Effect of Post-Tensioning on Tolerances**."

The design team should be prepared to share predicted immediate and long-term building deflections and movements that will impact both the concrete construction and the subsequent cladding and interior finishes. Potential movement information could include the magnitude and timing of slab deflections due to dead and live loads; floor plate constrictions due to shrinkage and post-tensioning; and column shortening due to prolonged loads, creep, and shrinkage. The early communication of predicted building movements will allow the design and construction teams to plan for mitigating measures such as a slab topping allowance, cambered slabs, sloped columns, and/or locating slab edges outboard of specified locations. The motivating common goal will be to bridge tolerance disconnects between specifications within MasterFormat Division 03 (Concrete) and Divisions 08 (Doors and Windows) and 09 (Finishes). When these tolerances are not coordinated, or if mitigation plans are not in place, unproductive conflicts and expensive remediation tasks are often needed. Table 2.15.1 provides a possible example, but project-specific designer input and coordination will lead to the most productive outcome.

Lastly, note that **ACI 318 PLUS** connects ACI 318 compliance requirements to **ACI 301-20** specification requirements, so it is a useful tool for designers to ensure compliance requirements are included in the project documents. ACI 301-20 contains a Mandatory Requirements Checklist, which lists information that must be specified in the project documents. If not specifically stated in the project documents, a general reference to ACI 301-20 will not make the requirement applicable.

Table 2.15.1: An example of predicted structural movements for a building project (all values in inches)

	Midpanel vertical slab deflection	Initial	3 months	6 months	12 months	24 months
A	Corner panel	–3/4	–1-1/2	–1-5/8	–1-3/4	–2
	Edge panel	–1/2	–1	–1-1/8	–1-1/4	–1-3/8
	Interior panel	–3/8	–3/4	–7/8	–1	–1-1/8
B	**Edge vertical deflection**	**Initial**	**3 months**	**6 months**	**12 months**	**24 months**
	Corner panel	–1/4	–1/2	–5/8	–5/8	–5/8
	Edge panel	–1/8	–1/4	–1/4	–3/8	–3/8
	Cantilever balcony slab (slab span parallel to framing span)	+1/8	+1/4	+1/4	+3/8	+3/8
	Cantilever balcony slab (slab span perpendicular to framing span)	–1/4	–1/2	–5/8	–5/8	–5/8
C	**Movement due to post-tensioning**	**Initial**	**3 months**	**6 months**	**12 months**	**24 months**
	Perimeter edge horizontal translation	0	–3/4	–7/8	–1	–1-1/8
	Perimeter column tilt	0	–3/4	–7/8	–1	–1-1/8
D	**Window/door header deflection**	**Initial**	**3 months**	**6 months**	**12 months**	**24 months**
	Openings in walls	–1/8	–1/4	–3/8	–1/2	–1/2
	Slab-to-slab openings	Refer to midpanel vertical slab deflections above.				
E	**Column shortening**					
		Not applicable to this building.				

American Society of Concrete Contractors (ASCC)

ASCC Position Statements address many constructability issues. For example, ASCC Position Statement #6 addresses flatness and levelness coordination concerns. This document suggests an allowance be established to address this tolerance concern. The document has been endorsed by six other construction associations. In his presentation for ACI's Constructability Series: Coordination and Completeness of Structural Construction Documents, Bruce Suprenant, Former Technical Director of ASCC, recommends an increase of 20 to 30% in design fees to improve constructability through the coordination and completion of drawings. Improvements in productivity (reducing construction schedule, field labor and RFIs, and change orders) will more than offset the higher design fee.

Project delivery methods can affect project documentation, coordination, and completeness. Suprenant further suggests the following considerations:

- Design-bid-build is the historical method of construction where contractor/designer collaboration is restricted. The design schedule and budget should allow for fully coordinated and complete construction documents to be issued for bidding. Unless the documents are complete and coordinated, productivity will likely suffer, and the constructability of design may fall short of expectations.
- The design-build delivery method typically involves the design professionals working directly for the contractor. The contractor sets the design and construction schedules to meet the

owner's requirements. Often, this means all construction documents are not complete when construction is started.

- Integrated project delivery and contractor/designer collaboration approaches will often mean that all construction documents are not complete at the time construction is started.
- The fast-track delivery method will start construction before the entire building design is complete. The owner must assume the risk for the construction documents that will not be coordinated or complete prior to construction.

ASTM International

Operable partitions installed between concrete slabs can be particularly problematic. **ASTM E557, Standard Guide for Architectural Design and Installation Practices for Sound Isolation between Spaces Separated by Operable Partitions**, addresses tolerance concerns and requirements to address the necessary coordination required for successful installations.

This chapter summarizes the attempts by many organizations to address a consistent barrier to improving productivity: poor coordination and incomplete construction documents. Remember, constructability drops to zero when the contractor does not know what to construct (when the documents are incomplete or not properly coordinated). And the outcomes—confrontation, delays, and contested change orders—cause all stakeholders to suffer. If the concrete industry can improve concrete construction productivity by providing fully coordinated and complete construction documents, all stakeholders will benefit.

2.16 SUMMARY OF CONSTRUCTABLE DESIGN PRINCIPLES

For concrete projects, improving productivity through constructability by design is a series of broad concepts. Constructability allows a project to be built faster, requiring fewer RFIs and field changes, while maximizing labor and crew productivities. Constructability embraces an owner's goals and architectural objectives. Highly constructable projects allow the concrete contractor to plan in detail, efficiently use modern construction systems, achieve fast and predictable outcomes, help finishing trades that follow to start earlier, and minimize trade tolerance conflicts requiring rework. All these concepts deliver cost-effective results to the owner due to the realized speed and productivity gains.

The Constructability Blueprint, "Constructable Design Principles" acknowledges regional, local, and contractor specific variations will exist in one's view of constructability. There are many variables at play, including weather, contractor experiences, contract risk, owner payment practices, local construction culture, availability of resources including labor knowhow, materials, and equipment. While "Constructable Design Principles" will not substitute for early, ethical, and engaged contractor-designer collaboration to improve concrete construction productivity, the document can provide guidance, insights, and serve as a reference for designers.

The ACI Center of Excellence for Advancing Productivity (PRO) envisions the Constructability Blueprint to be "ever evolving," with new technologies, systems, construction and design practices and clarifications of concepts added over time. Industry stakeholders that find the "Constructable Design Principles" of value, may possess their own experiences, knowledge, or access other documents that can expand these contents. You are encouraged to submit your contributions and references to: **phil.diekemper@concreteproductivity.com**.

PRO extends its gratitude to PRO members, whose contributions have supported the creation of this document and provide for all in the concrete industry to download the digital document without restrictions and without fee. Members and contact information are noted on the Member Acknowledgment page of this document.

Further information on constructability, PRO activities, and PRO membership is available here: **PRO: An ACI Center of Excellence for Advancing Productivity**.

PRO PROUDLY RECOGNIZES

Founding Member: American Concrete Institute

Members:

PRO

An ACI Center of Excellence for Advancing Productivity

Launched in 2023, **PRO: An ACI Center of Excellence for Advancing Productivity** will work as a catalyst for solving the barriers to constructability to advance concrete construction productivity. PRO will collaborate with designers, materials suppliers, and contractors to identify and resolve issues that negatively impact productivity in concrete construction.

38800 Country Club Drive
Farmington Hills, MI
48331-3439 USA

+1.248.516.1590

www.concreteproductivity.org

Phil Diekemper, Executive Director
+1.248.479.4451
phil.diekemper@concreteproductivity.org

Founded in 2023 by the American Concrete Institute