Updated 10/24/2024

Constructability BLUEPRINT

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An ACI Center of Excellence
for Advancing Productivity

www.concreteproductivity.org

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Baker Construction is the nation's largest commercial concrete contractor, specializing in industrial, industrial distribution, structural, and restoration construction. Founded in 1968 and headquartered in Monroe, OH, Baker has nearly 7,500 co-workers with a presence across the U.S. and the Bahamas.

SILVER

CECO

+1.816.459.7000
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Ceco is a nationwide leader in cast-in-place concrete construction. Originating in 1912 in Omaha, NE, Ceco is now headquartered in Kansas City, MO, with 19 locations across the country. Ceco Concrete Construction is backed by the global strength and resources of their parent company, The Heico Companies. Ceco Concrete Construction is also proud to be certified as a WBENC business. WBENC's national standard of certification is a meticulous process involving an in-depth review of the business that is seeking certification to confirm that the business is at least 51% owned, operated, and controlled by a woman or women.

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

The **Conco Companies** began in 1959 and are headquartered in the Bay Area in California, serving a wide range of areas on the West Coast, while also performing shotcrete and rebar installations. Conco's mission is to be the best supplier of concrete services in the Western United States and to bring expertise, experience and quality to each project.

+1.239.210.6519
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Somero® Enterprises, Inc. is a leading manufacturer of technologically advanced Laser Screed® equipment and associated machinery. The company was founded in 1986 with a Global Headquarters and Somero® Concrete Institute & Training Facility in Fort Myers, Florida, and additional offices in Michigan, England, Australia, Belgium and India, as well as, an extensive domestic and international dealer network. Somero® offers a wide portfolio of products that cover concrete slab placements in all types of construction projects, horizontal and structural. In addition to equipment and software products, the company also supports its global customer-base with timely parts delivery, on-site support and best-in-class training solutions.

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Cemex is a global building materials company that provides high-quality products and reliable services with a rich history of improving the wellbeing of those it serves through innovative building solutions, efficiency advancements and sustainability efforts. Its U.S. network includes 8 cement plants, close to 50 strategically located cement terminals, nearly 50 aggregate quarries and more than 280 ready-mix concrete plants. Cemex US has been repeatedly recognized for its efforts in sustainability and energy management, including earning U.S. EPA ENERGY STAR® Partner of the Year consecutively since 2019.

AFFILIATED

+1.866.788.2722
https://ascconline.org/

Founded in 1964 and headquartered in St. Louis, Mo., the **American Society of Concrete Contractors (ASCC)** is a non-profit association developed by concrete contractors for concrete contractors to provide a unified voice for the industry. Since its beginnings, the ASCC has grown to represent approximately 750 companies worldwide, providing unmatched support for industry knowledge, best practices and recognition. Members of the ASCC represent concrete and general contracting firms, manufacturers, suppliers, designers and other concrete industry professionals both in the field and in the office. This powerful organization remains 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.

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.

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An ACI Center of Excellence
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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.

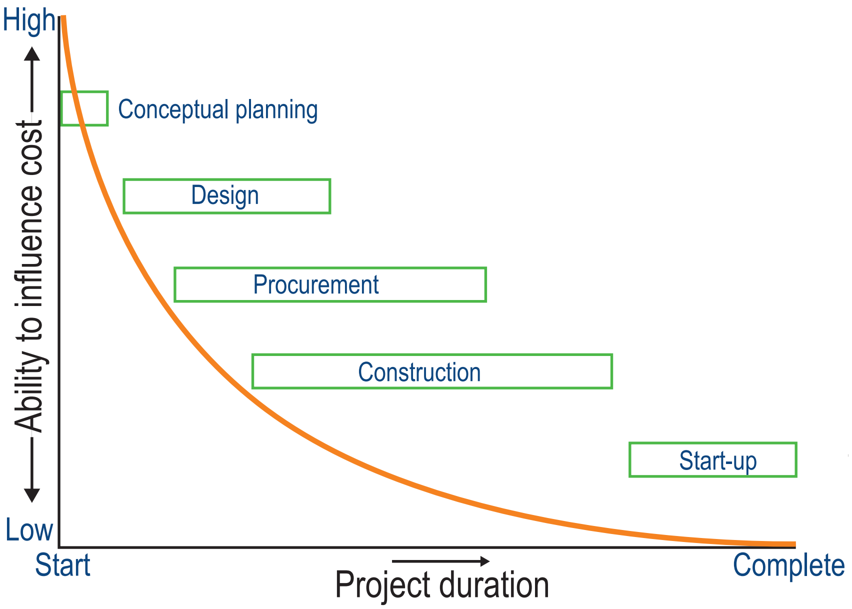

Fig. 1.1.1: The ability to influence the final cost of a project decreases rapidly with each phase of the project ("Constructability: A Primer, Construction Industry Institute," Austin, TX, 1986, 24 pp.)

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.

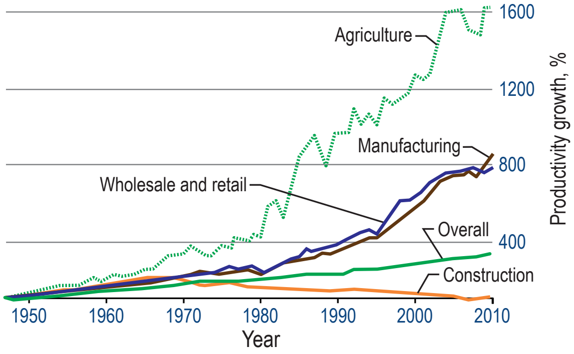

Fig. 1.3.1: For decades, construction productivity has experienced little or no growth, while other sectors have experienced massive gains in productivity. (Barbosa, F. et al., "Reinventing Construction: A Route to Higher Productivity," McKinsey Global Institute, Feb. 2017, 158 pp.)

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.

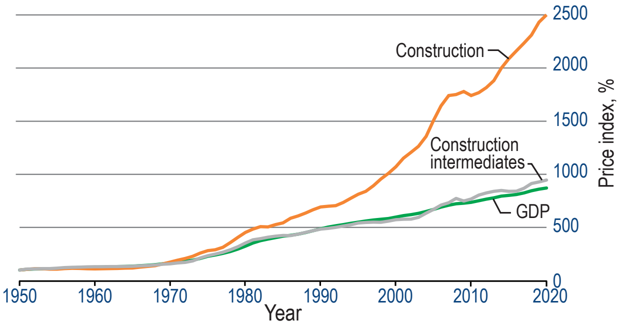

Fig. 1.3.2: Price indexes for construction, construction intermediates, and GDP, from 1950 to 2020. (Goolsbee, A., and Syverson, C., "The Strange and Awful Path of Productivity in the U.S. Construction Sector, Working Paper 30845," National Bureau of Economic Research, Jan. 2023, Revised Feb. 2023, 27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

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[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).

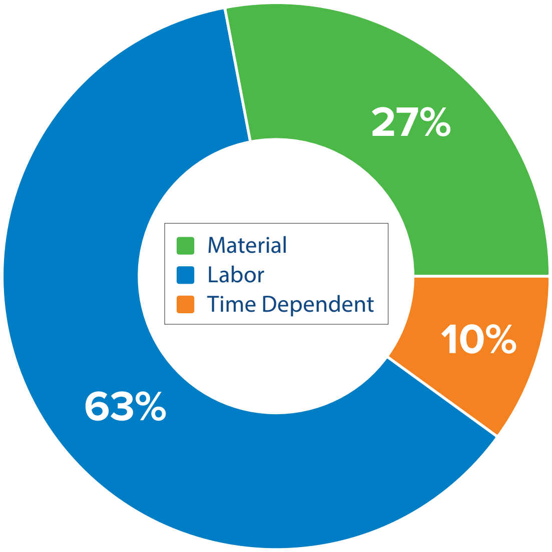

Fig. 1.4.1: The cost of labor comprises more than twice the cost of materials for a concrete construction project.

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.

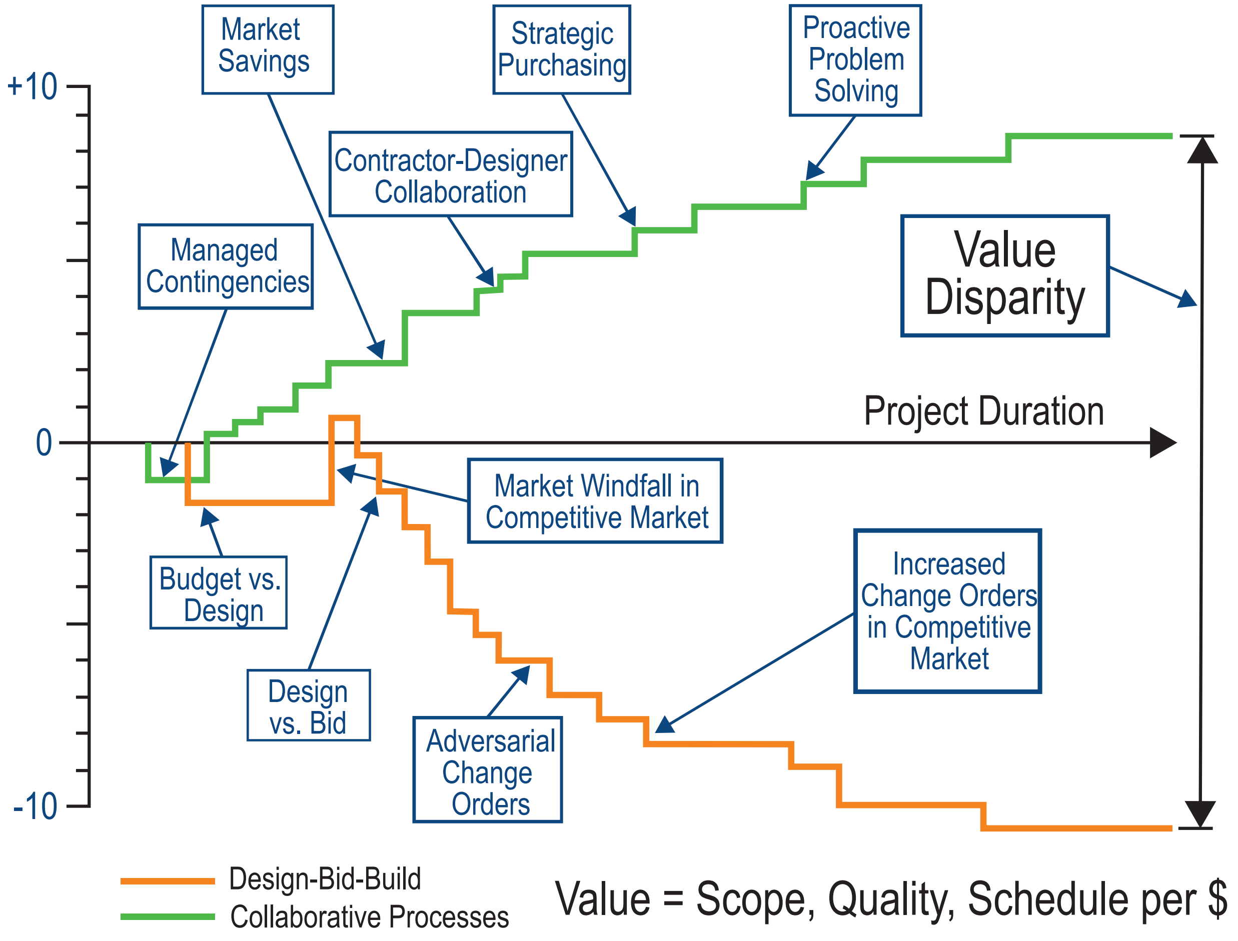

Fig. 1.5.1: Value (scope, quality, and schedule enhancements per dollar spent) can be lost within an adversarial bid environment—even in a competitive market, where significant windfalls at 'bid-time' are sometimes captured. (Bryson, B.W., and Yetmen, C., The Owner's Dilemma: Driving Success and Innovation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

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[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.

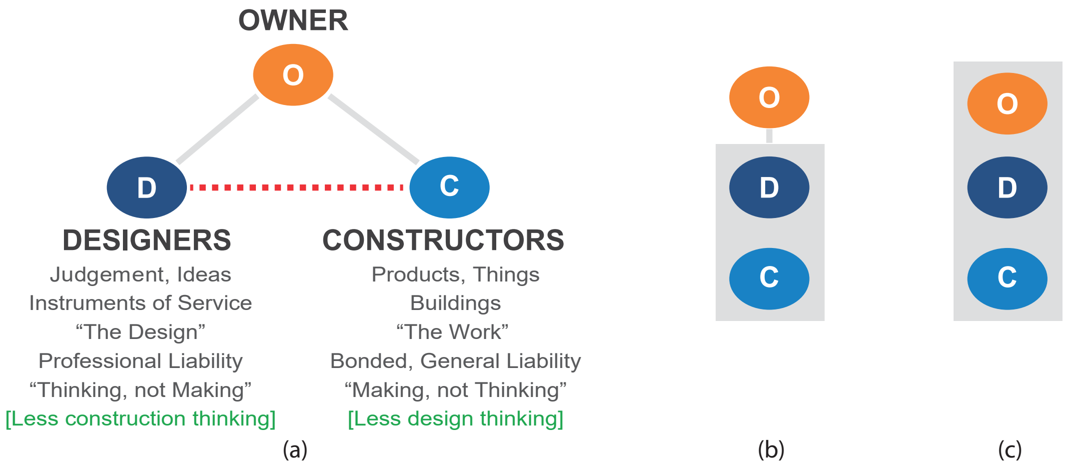

Fig. 1.6.1: The owner must work with design and constructor teams, each with its unique goals, responsibilities, purpose, and mindset: (a) Traditional Design-Bid-Build delivery creates silos and results in inefficient communication; (b) Design-Build delivery improves communication between designers and 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.

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[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.

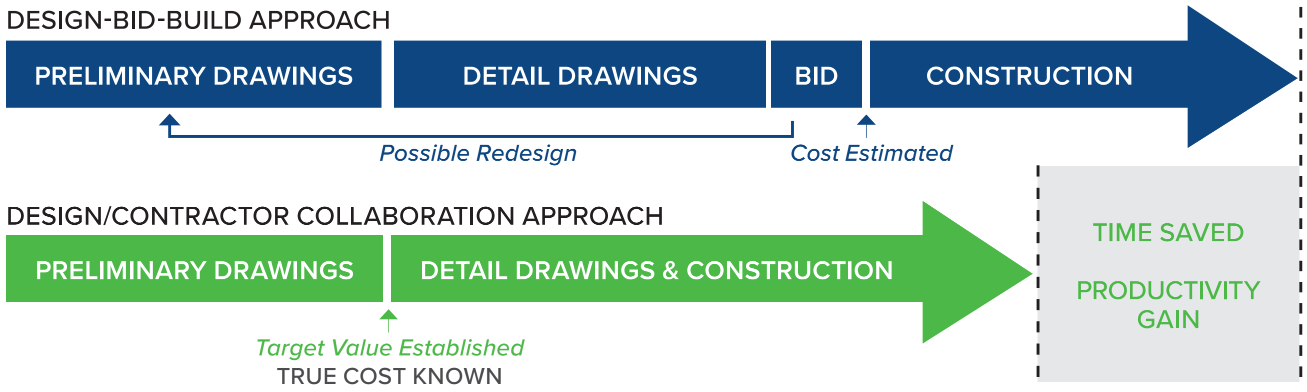

Fig. 1.7.1: IPD adds value through collaboration.

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).

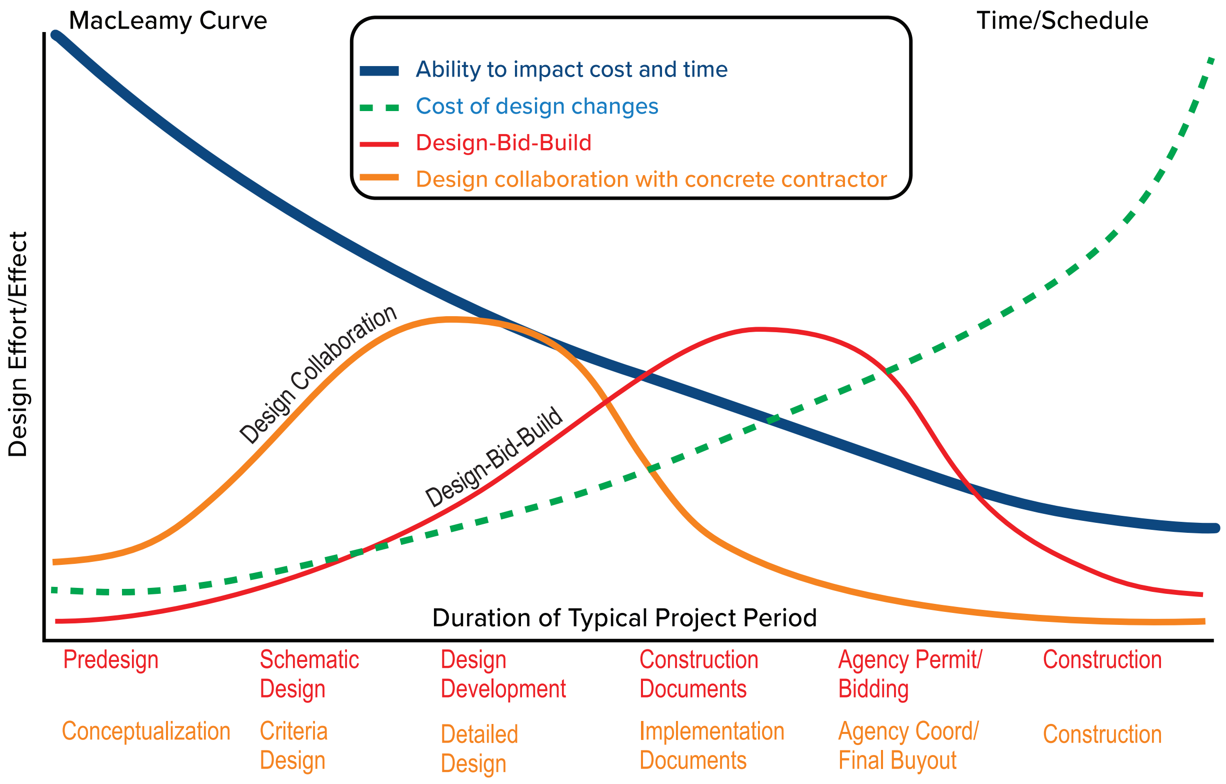

Fig. 1.7.2: The MacLeamy Curve demonstrates the benefits of early collaboration on decisions (after The Owner's Dilemma*).*

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.

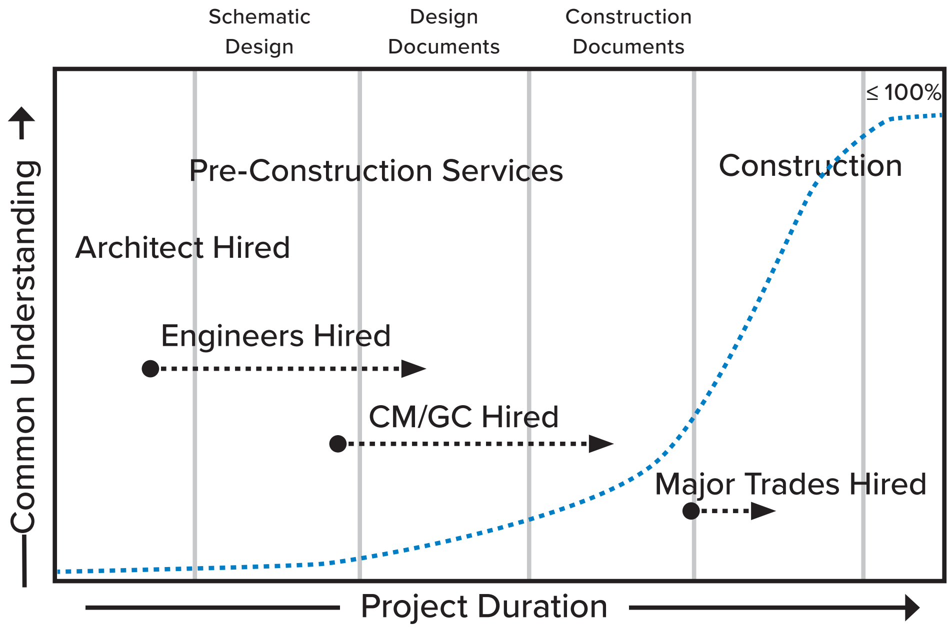

Fig. 1.7.3: Illustration of the significant intelligence that is added to a project when the major trades are hired, often after preconstruction design and planning is nearly complete. The late addition of the major trades reflects a missed opportunity to improve constructability during design.

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.

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SECTION 2: CONSTRUCTABLE DESIGN PRINCIPLES*

2.1 Pathways toward Constructable Design

2.2 Code-Compliant Design versus Code-Constructable Design

2.3 Permanent Material versus Construction Labor and Time

2.4 Where to Start as a Designer

2.5 Horizontal Framing

2.6 Formwork Logic

2.7 Reinforcement Logic

2.8 Summary of Constructable Design Principles

**2.9 through 2.16 to be published later.*

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.

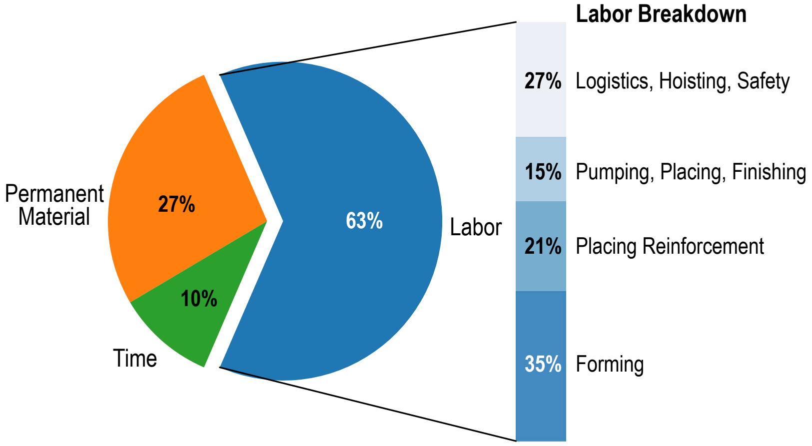


Fig. 2.3.1: A recent analysis of a reinforced concrete building structure showed that labor comprised most of the cost of construction, while permanent material and time (time-dependent costs such as equipment rental) comprised only 27% and 10% of the total cost of construction, respectively. Note: percentages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

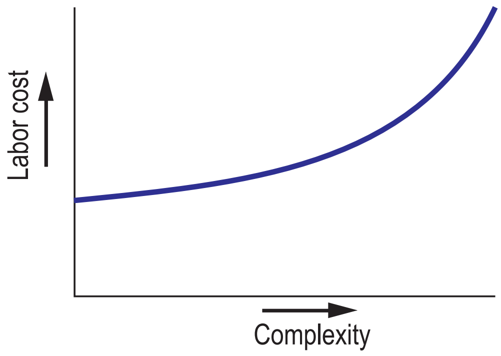


Fig. 2.3.2: Labor costs can increase exponentially with increasing complexity.

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).

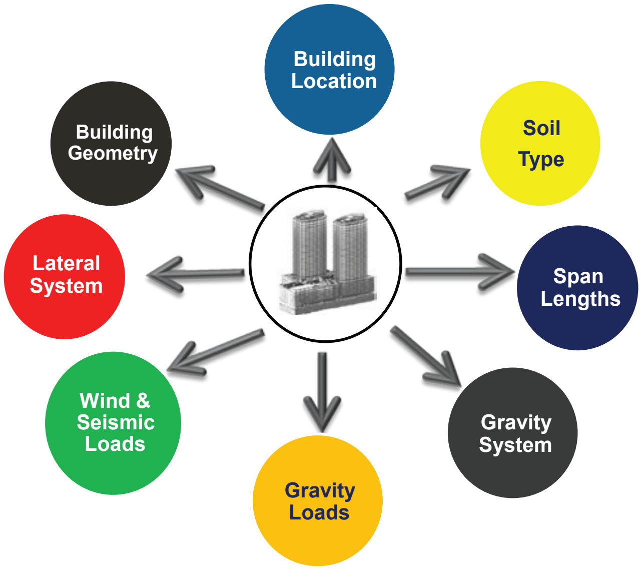


Fig. 2.4.1: Factors affecting material quantities in a concrete building structure. (Image courtesy of CKC.)

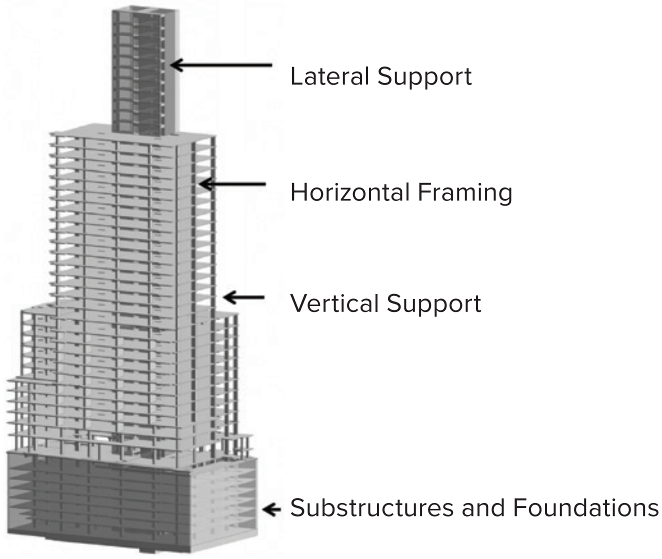


Fig. 2.4.2: Schematic illustration of primary structural components in a mid- or high-rise structure. (Image courtesy of CKC.)

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 formwork 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.

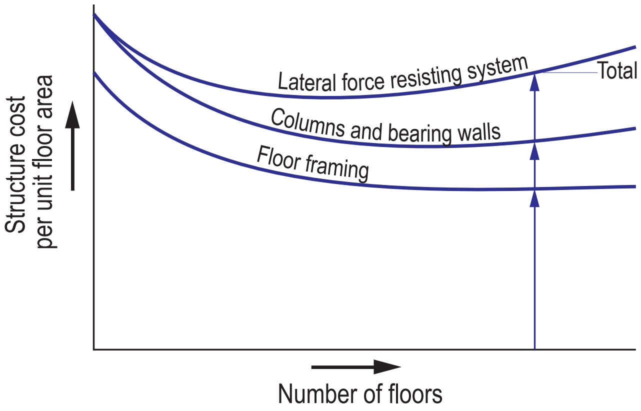


Fig. 2.4.3: Schematic illustration of relative costs of three structural elements as a function of building height. Labor costs will decrease to an optimum value as workers gain experience and mobilization costs become less of a factor. Thereafter, the unit cost of floor framing will remain constant 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.

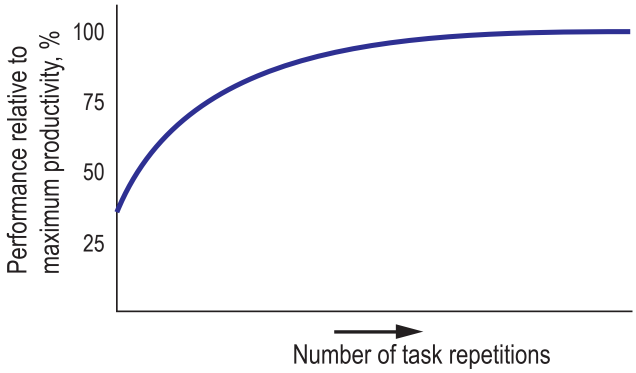
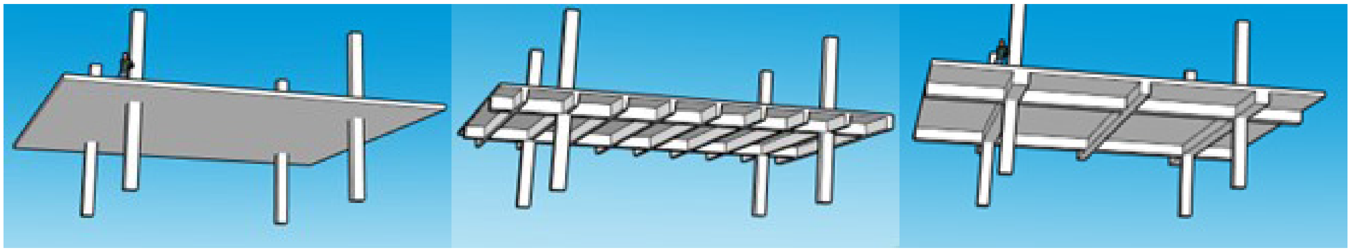


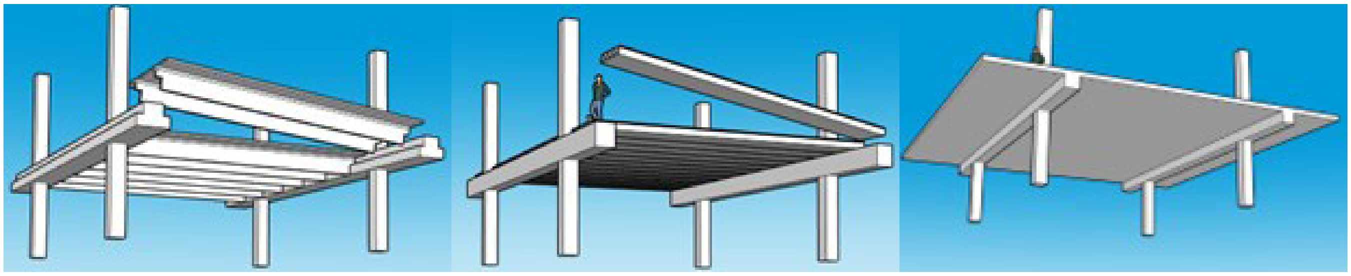
Fig. 2.4.4: Schematic learning curve for a formwork crew. The crew's productivity plateaus after a rapid increase as they become familiar with the formwork and structural systems.

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.



Flat plate Pan slab Slab and beam, mild reinforcing



Precast double tees and inverted tees Precast hollow core slab Slab and beam, PT reinforcing

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.

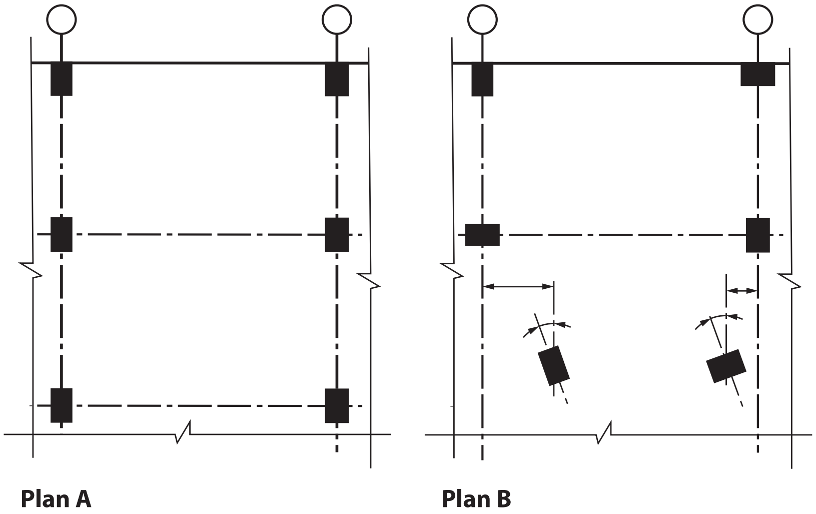


Fig. 2.6.1: Consistency and repeatability are critical for constructability. In contrast to Plan B, the columns in Plan A have consistent size and orientation, allowing the contactor to design and furnish advanced table panel floor formwork and reduce likelihood of layout errors.

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.

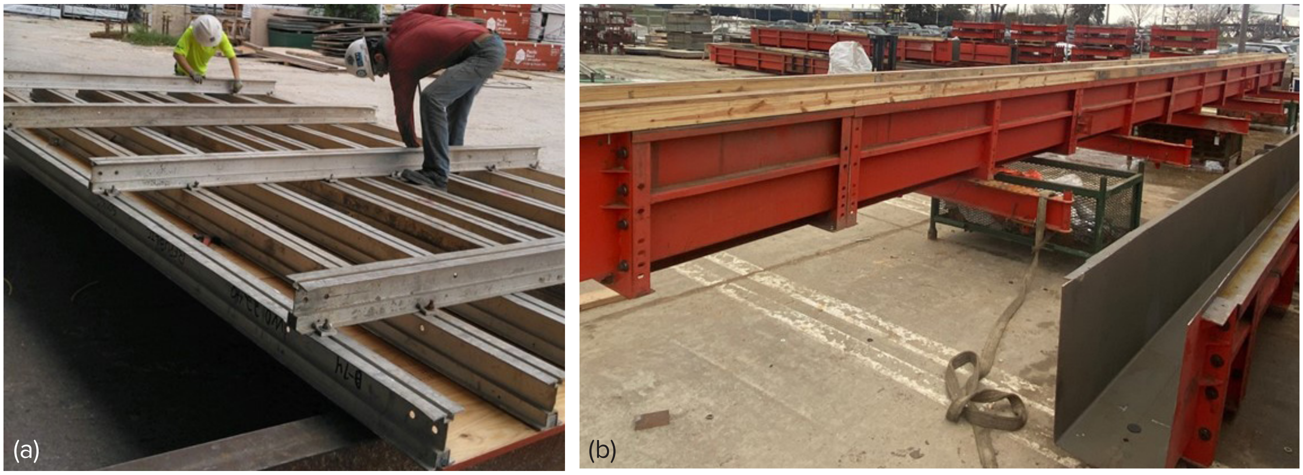


Fig. 2.6.3: Workers engage in the make-up of formwork: (a) a gang panel using standardized components; and (b) a 60 ft long steel beam form with drafted sides. (Images courtesy of Ceco Concrete Construction.)

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.

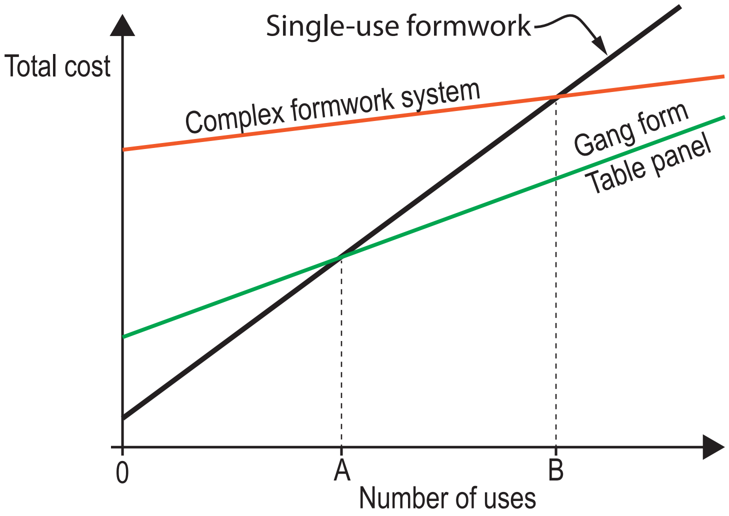


Fig. 2.6.4: A schematic representation of a contractor's evaluation of the financial impacts of highly productive formwork applications on a project. Complex formwork systems include multi-use, high-production systems and/or self-climbing systems.

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.

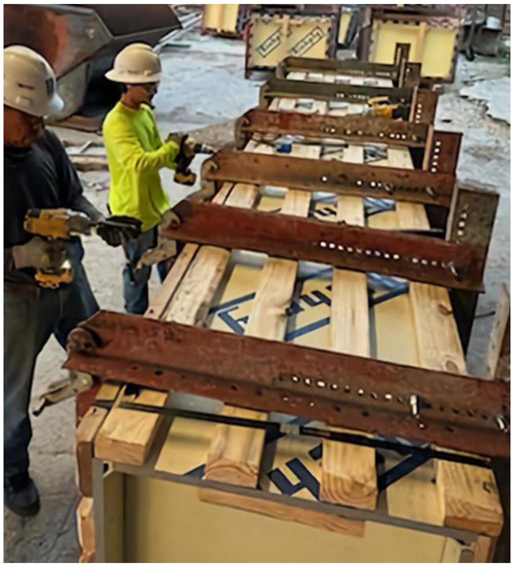


Fig. 2.6.7: Workers engaged in the assembly (make-up) of a column form. (Image courtesy of Ceco Concrete Construction.)

(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.)

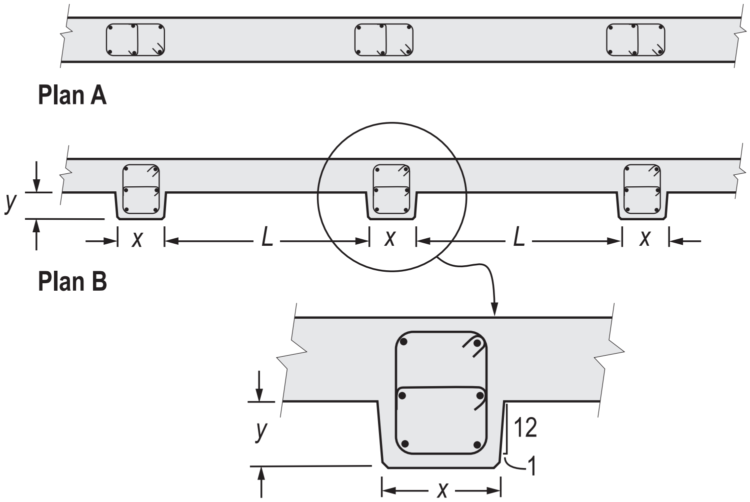


Fig. 2.6.10: Pilasters increase the complexity of wall formwork, thus diminishing construction productivity. In the preferred alternative (Plan A), pilaster reinforcement is contained within a wall and the wall formwork has a planar surface. If pilasters must extend beyond one face of a wall (Plan B), 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.)

Fig. 2.6.12: Workers remove deck formwork before installing reshores. (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.

(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.)

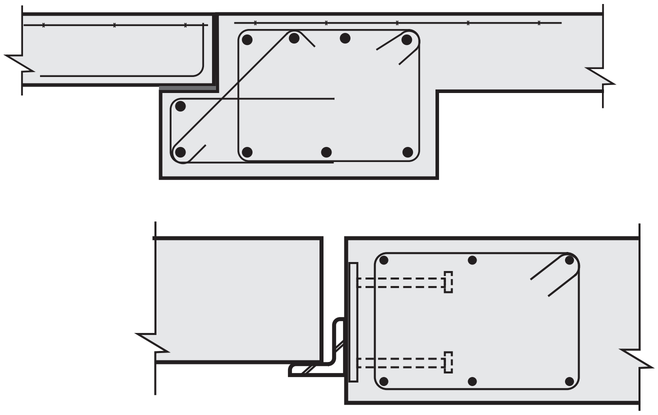


Fig. 2.6.14: Examples of expansion joint details for PT construction. If required to maintain a diaphragm, reinforcing bars with slip connecters can be included and grouted after initial shrinkage is complete.

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.)

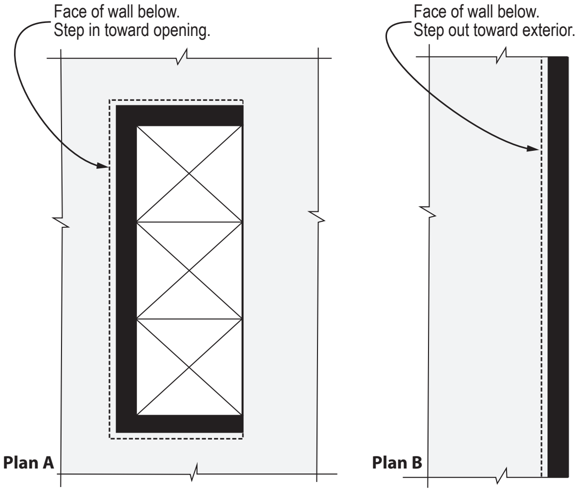


Fig. 2.6.18: Wall faces defining opening edges and exterior of structure are normally held over the building height. Reductions in wall thickness are therefore made by shifting one form face toward an opening or the building exterior.

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

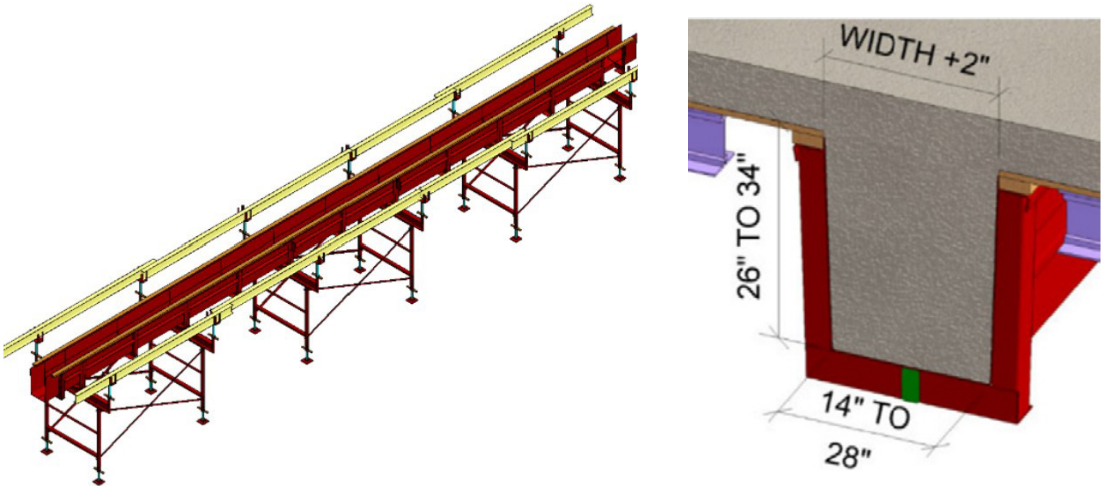


Fig. 2.6.20: Single-piece forms are commonly used to construct repetitive long-span beams in parking structures. The form sides of such systems can resist fresh concrete pressures without the need for tie rods. (Image courtesy of Ceco Concrete Construction.)

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.

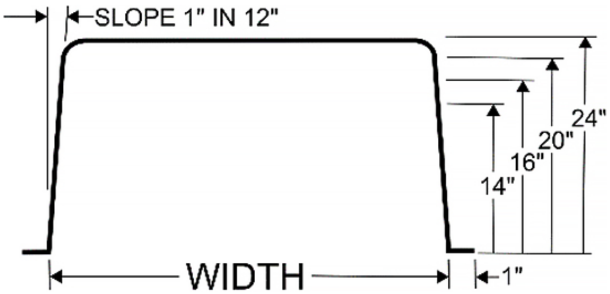


Fig. 2.6.21: Pan systems are available in widths of 20, 30, 53, and 66 in. The beam width can be varied by adjusting the gap between pans. (Illustration courtesy of Ceco Concrete Construction.)

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

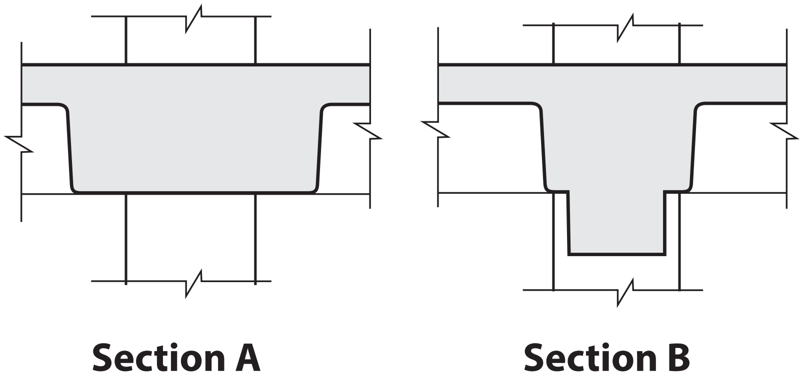


Fig. 2.6.23: Pan systems are most efficiently applied when the floor framing has a consistent soffit elevation. Interior and exterior beams and girders should match the pan depth plus slab thickness whenever possible (Section A). If girders are designed with greater depth, the shored deck supporting 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)).

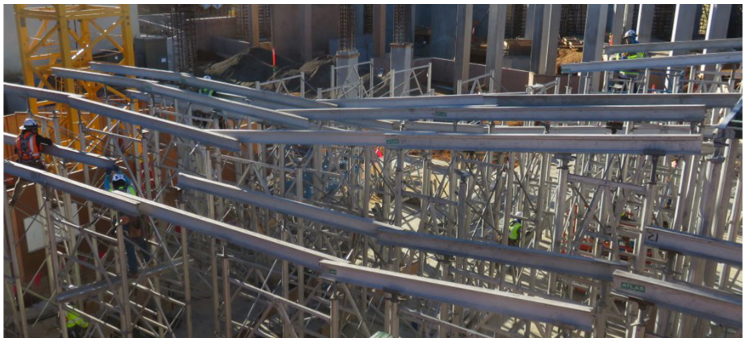
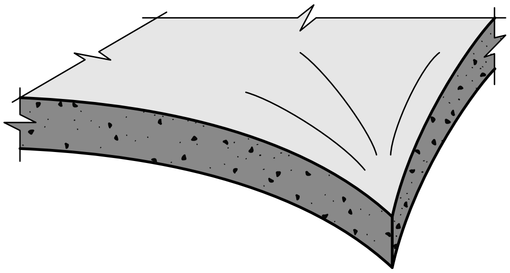
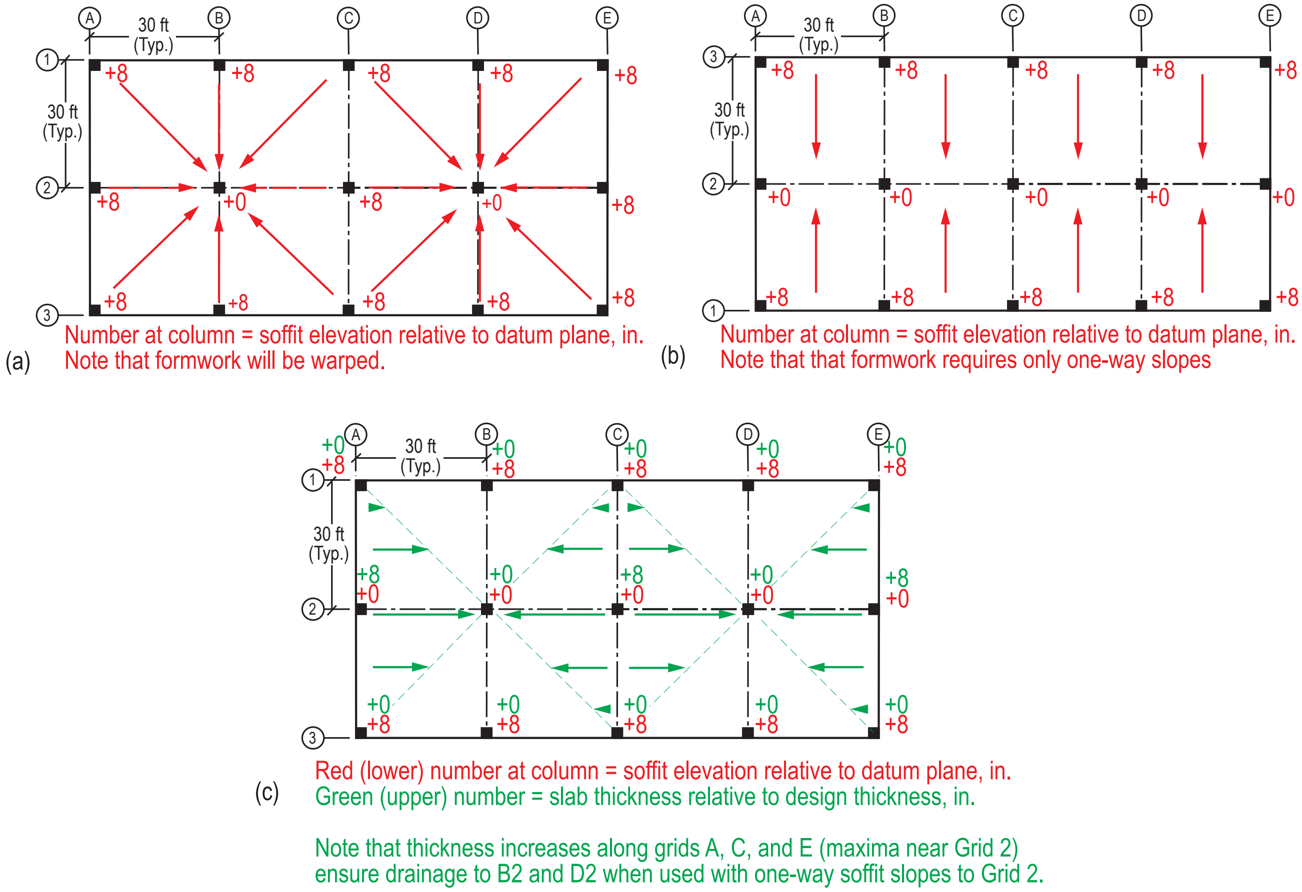


Fig. 2.6.28: Straight-soffit formwork elements are used to achieve a one-way slope transition with high shoring. While the formwork for such a transition is complex, it is more constructable than the formwork required to create a two-way slope or a warped slab. (Image courtesy of Hensel Phelps.)



Top and bottom surfaces are curved

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



(a) Number at column = soffit elevation relative to datum plane, in. Note that formwork will be warped.

(b) Number at column = soffit elevation relative to datum plane, in. Note that that formwork requires only one-way slopes

(c) Red (lower) number at column = soffit elevation relative to datum plane, in. Green (upper) number = slab thickness relative to design thickness, in.

Note that thickness increases along grids A, C, and E (maxima near Grid 2) ensure drainage to B2 and D2 when used with one-way soffit slopes to Grid 2.

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).

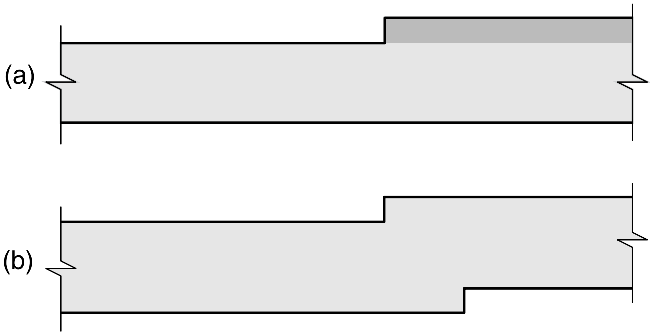


Fig. 2.6.32: Examples of slab transitions: (a) transition created by placement of a topping course; and (b) transition created using offsets at both the top surface and soffit of a slab.

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.

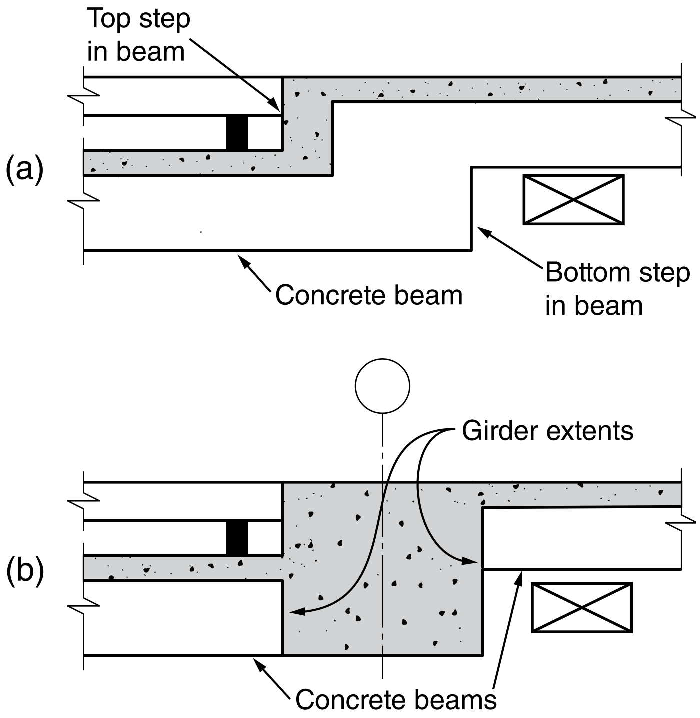


Fig. 2.6.35: Deep transitions in slab elevations: (a) equal transition depths should be provided for the top and soffit elevations; and (b) transitions should be located at the side of a beam or girder.

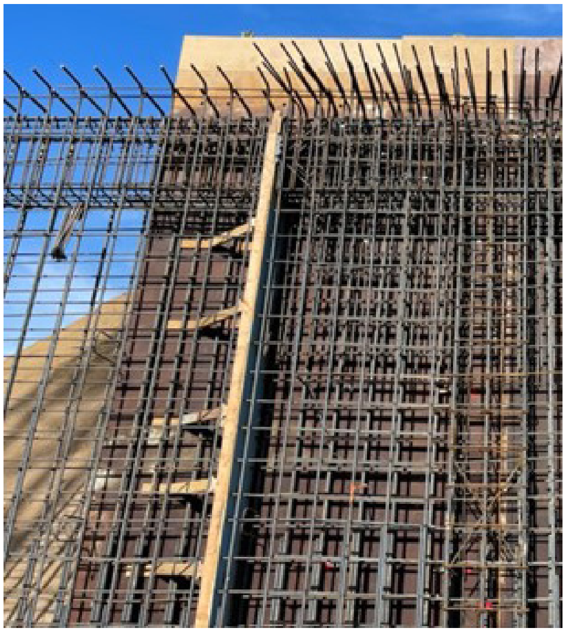


Fig. 2.6.36: A progress photo showing a wall with two layers of reinforcement penetrating the vertical formwork at a construction joint. Such joints are labor- and time-intensive to form and remove, so contractors seek to minimize such construction joints and reinforcing penetrations to improve constructability.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

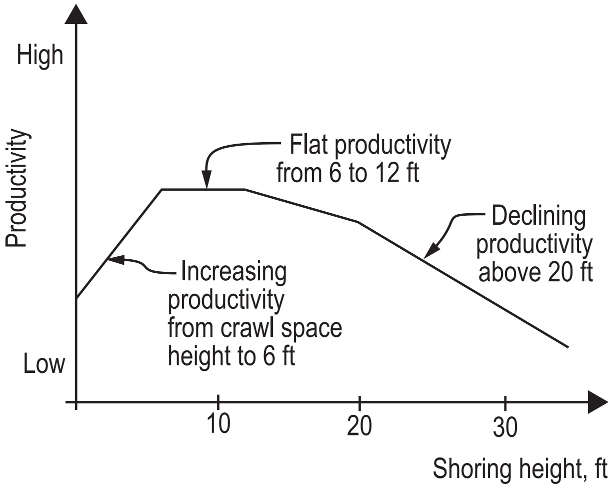


Fig. 2.6.37: Schematic illustration of the effect of shoring height on construction productivity.

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.

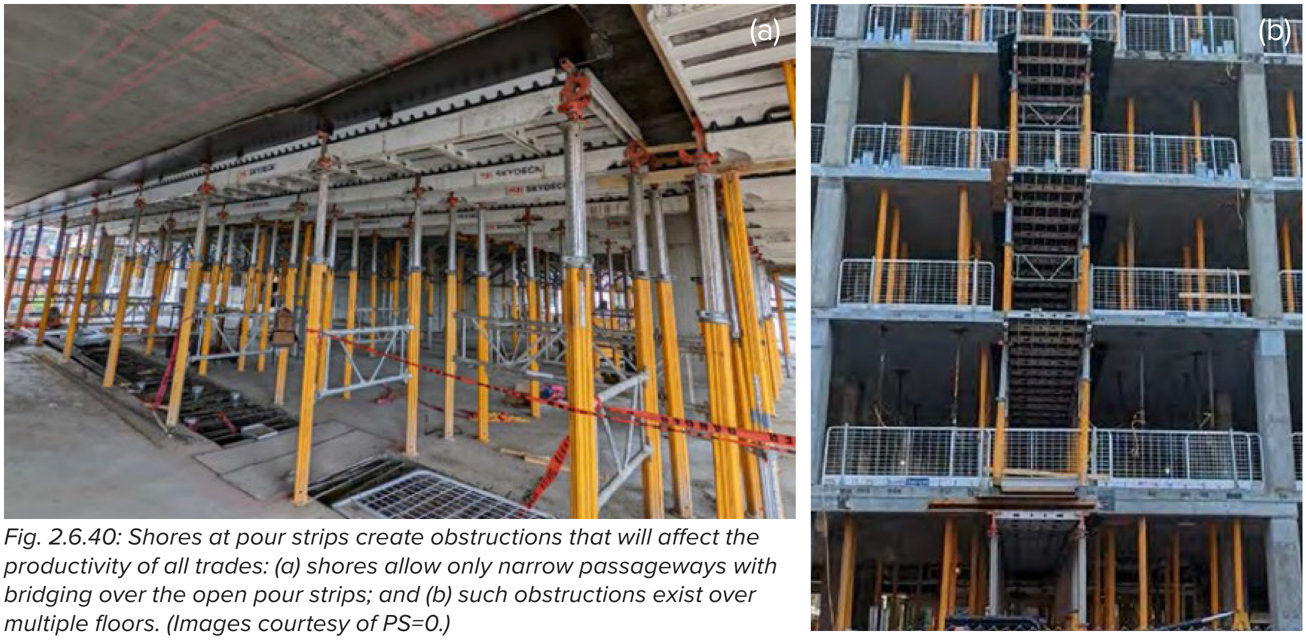


Fig. 2.6.40: Shores at pour strips create obstructions that will affect the productivity of all trades: (a) shores allow only narrow passageways with bridging over the open pour strips; and (b) such obstructions exist over multiple floors. (Images courtesy of PS=0.)

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.

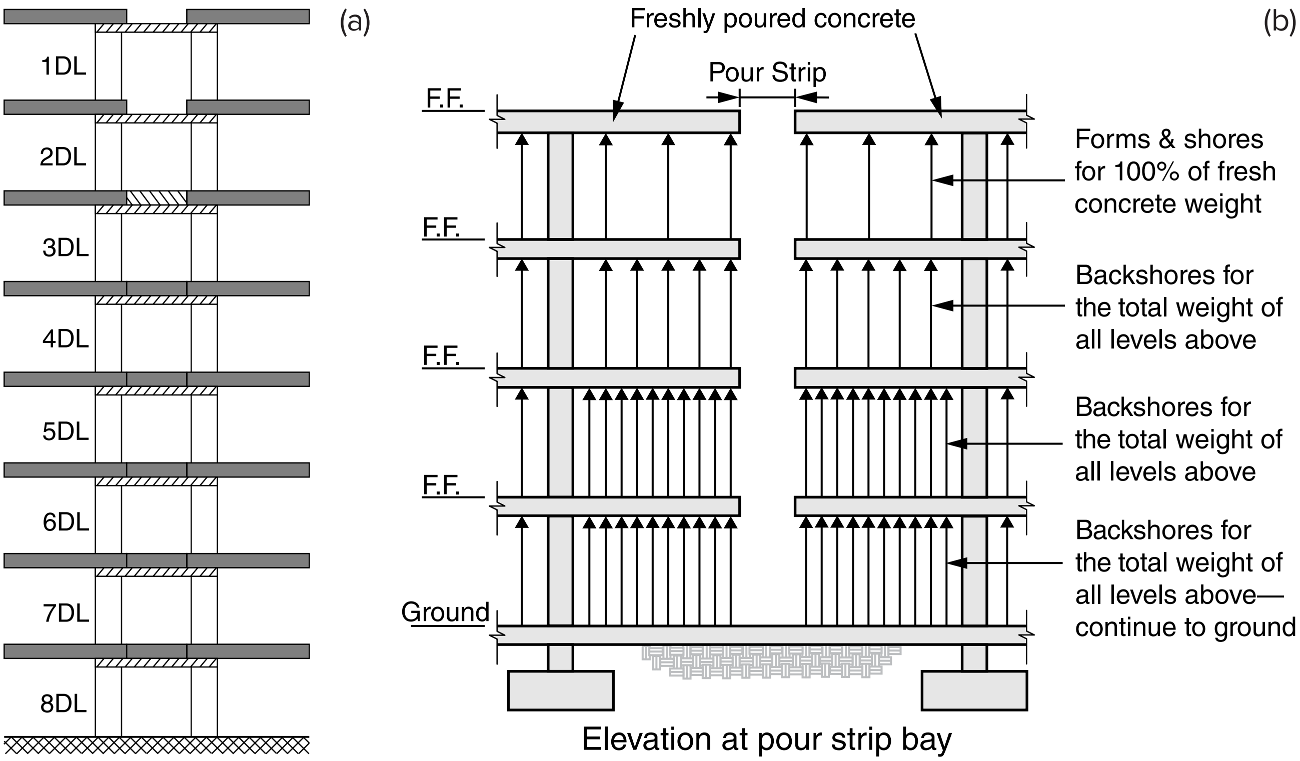
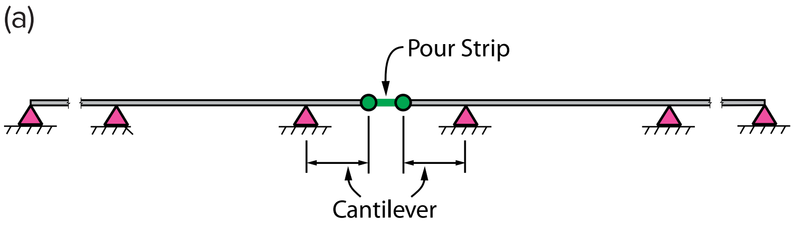


Fig. 2.6.41: Backshores supporting pour strips: (a) loads increase with every additional level (courtesy of Ceco Concrete Construction); and (b) the density of backshores increases with every additional level. (Image courtesy of the Post-Tensioning Institute.)

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.



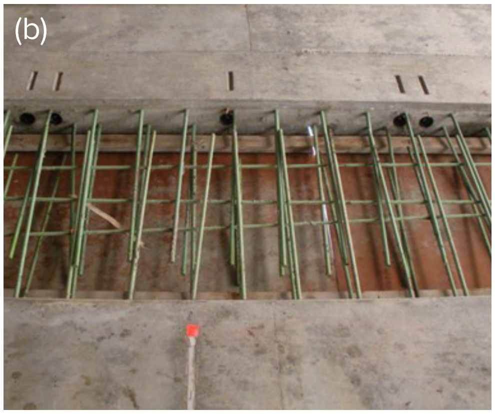
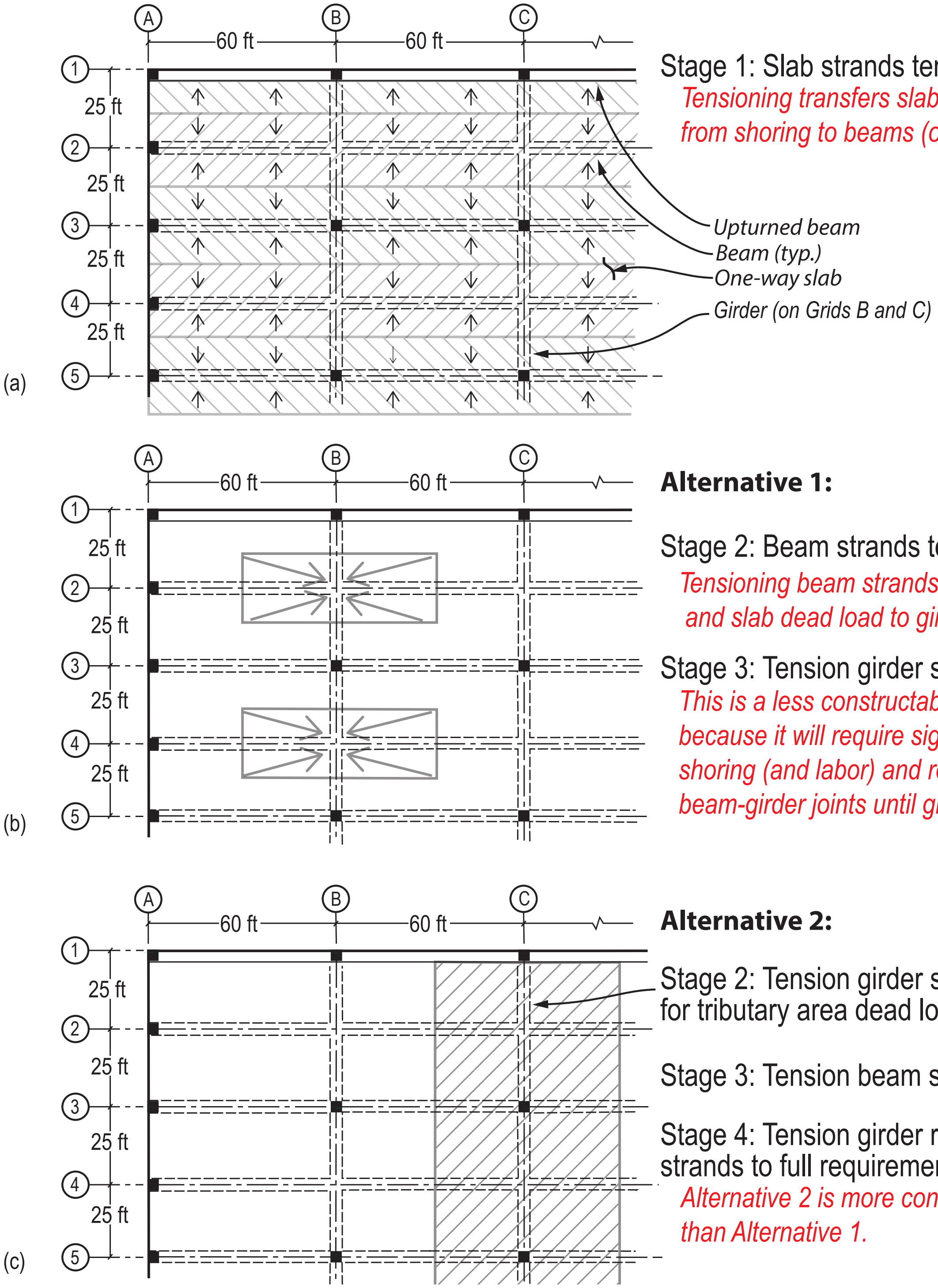


Fig. 2.6.42: Designing a pour strip as a simple span supported by PT cantilevers can help avoid the need for backshoring: (a) schematic model of a strip; and (b) the PT cantilevers are self-supporting. (Image courtesy of AMSYSCO.)

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.



Stage 1: Slab strands tensioned

Tensioning transfers slab dead load from shoring to beams (on Grids 1, 2, 3, 4, 5)

Alternative 1:

Stage 2: Beam strands tensioned.

Tensioning beam strands transfers beam and slab dead load to girder intersection.

Stage 3: Tension girder strands.

This is a less constructable alternative because it will require significant temporary shoring (and labor) and reshoring below the beam-girder joints until girders are tensioned.

Alternative 2:

Stage 2: Tension girder strands for tributary area dead load only.

Stage 3: Tension beam strands.

Stage 4: Tension girder remaining strands to full requirement.

Alternative 2 is more constructable than Alternative 1.

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

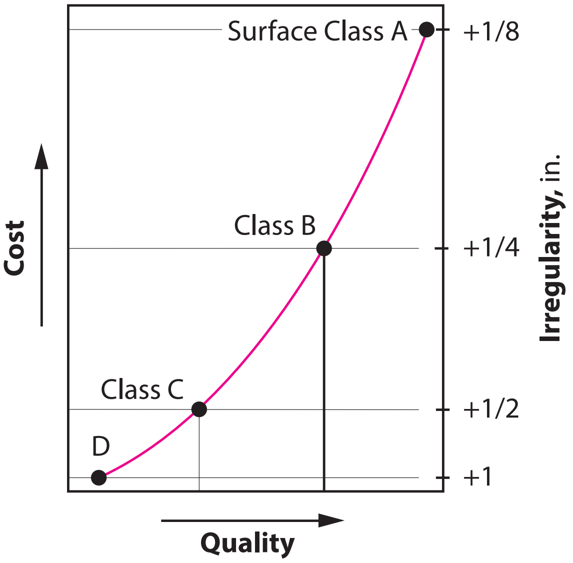
Note: Refer to ACI 435R-20 for source citations

(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.

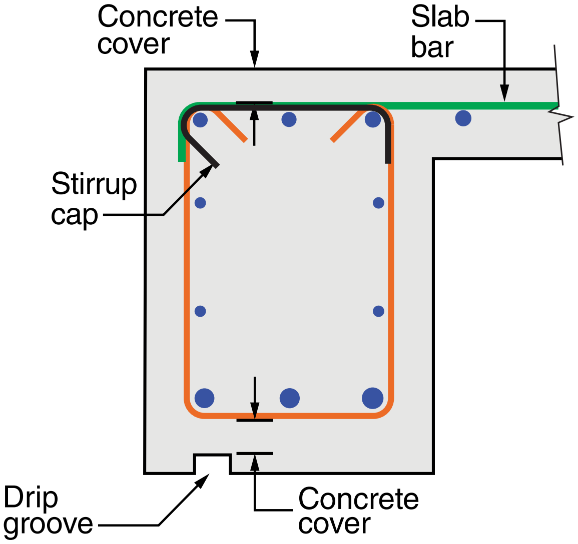


Fig. 2.7.4: Designers should be aware that drip grooves control the cover on exterior framing elements.

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.

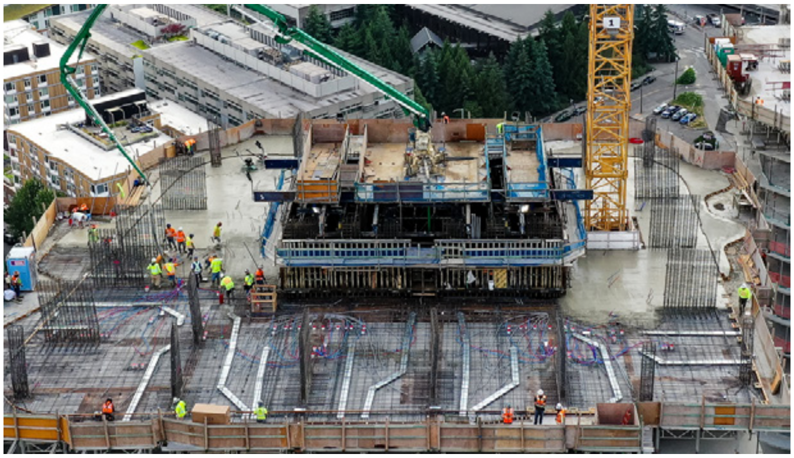
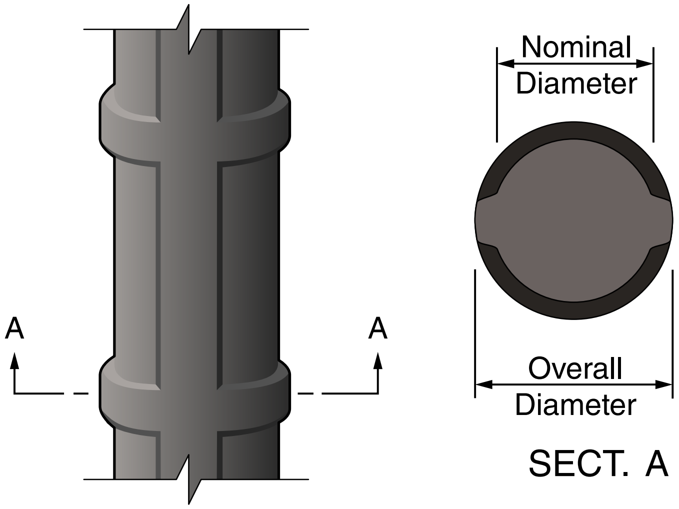


Fig. 2.7.6: Concrete placement on a floor structure. The structure will not be post-tensioned and the placement area is relatively small, so the contractor has elected to place concrete over the full floor area in a single pour. (Image courtesy of Ceco Concrete Construction.)

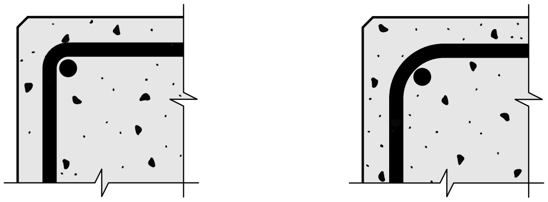
(d) Designers are encouraged to provide specific reinforcing details and cut sections for non-typical locations where congestion is a concern, including narrow beams, beam-column joints, or columns with more than 2% longitudinal reinforcement. This step will naturally reveal reinforcing bar constructability 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.)



Incorrect bend diameter illustrated in drawing

Correct bend diameter as fabricated and placed

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).

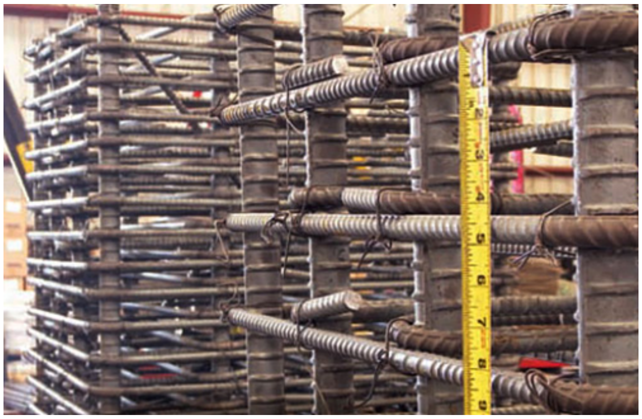


Fig. 2.7.10: Column cage mockups designed and fabricated using different grades of bars. The cage comprising HSRBs (foreground) required significantly less labor for bar placement and will allow much better flow of concrete between bars than would be required in a cage comprising Grade 60 bars (background).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

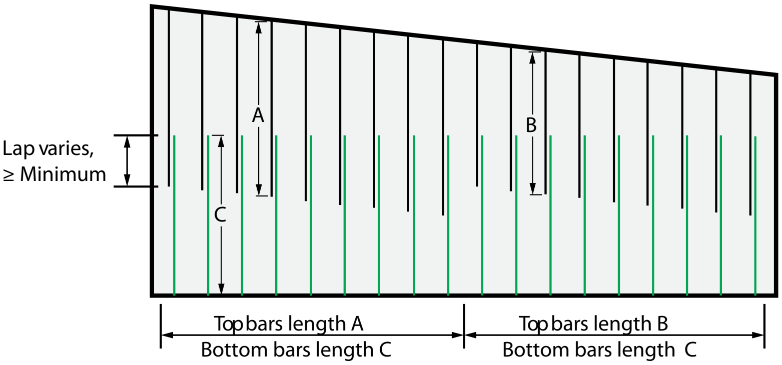


Fig. 2.7.11: The number of unique bars required for a project can be reduced by allowing lap lengths to vary. (Detail from "Design Guide for Economical Reinforced Concrete Structures.")

(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).

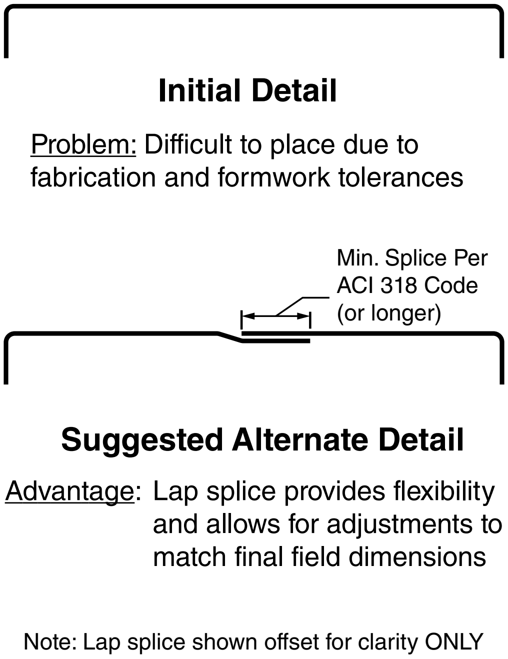


Fig. 2.7.12: Bars with double hooks create constructability issues. Lap splicing of bars allows for field adjustments and ensuring hooks have adequate cover. (Image courtesy of CRSI.)

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

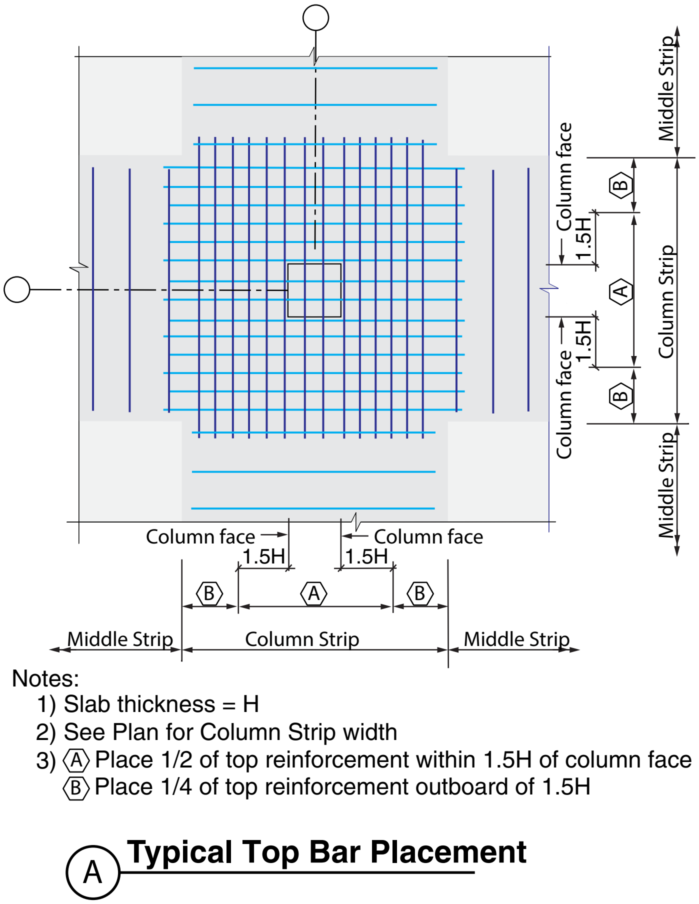


Fig. 2.7.14: An example of a detail that should be provided by the designer to address reinforcing bar placement at slab-column connections.

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

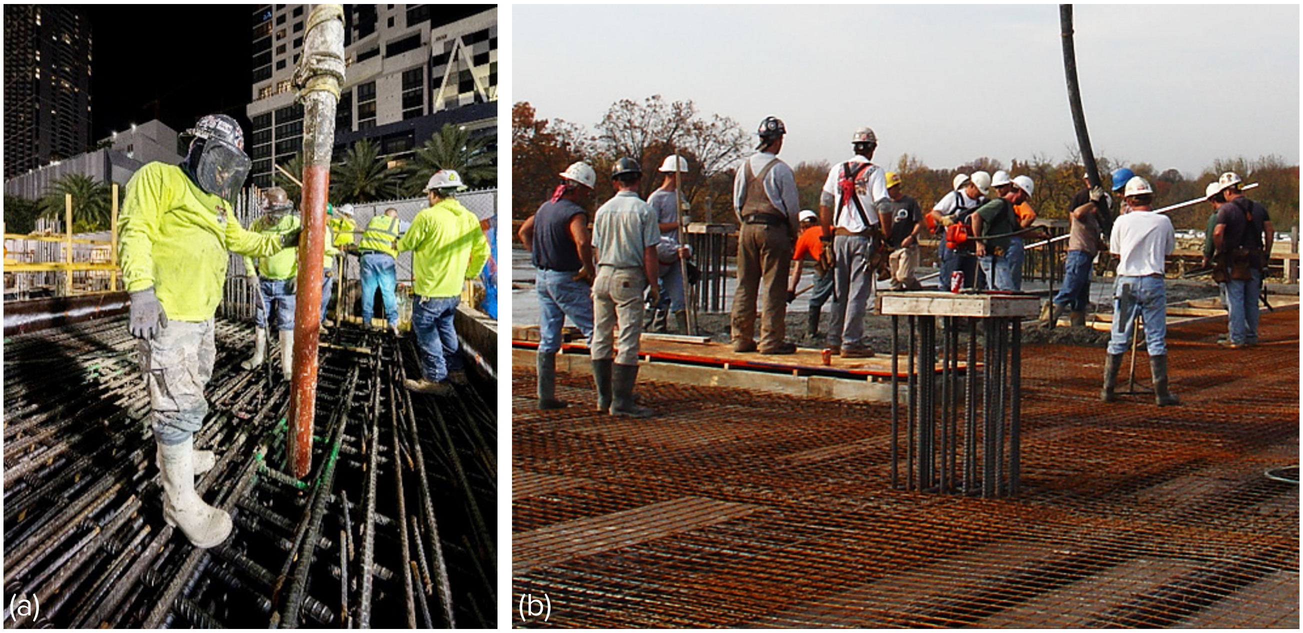
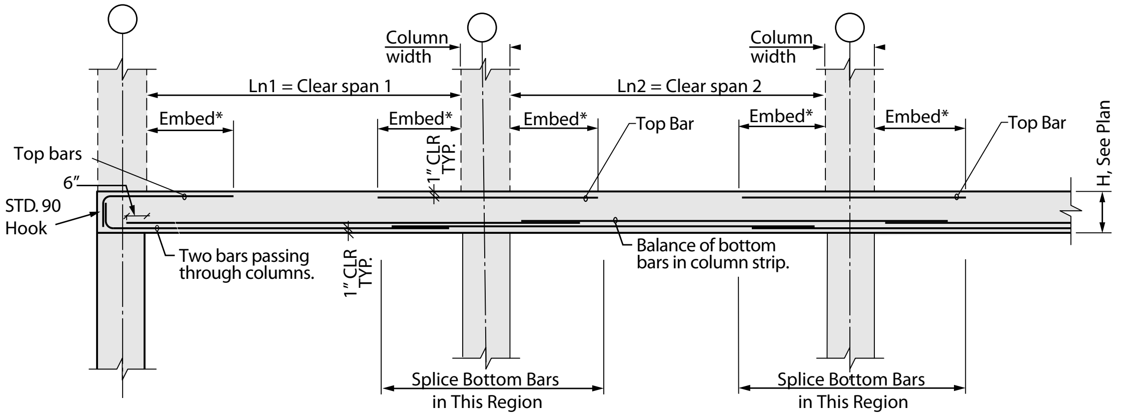


Fig. 2.7.15: Crews must walk on the reinforcing in thick slabs and foundation mats during concrete placements. Safe footing can be provided using: (a) grid of closely spaced reinforcing bars; or (b) welded-wire reinforcing placed on top of larger, more widely spaced bars. (Images courtesy of Ceco Concrete 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 **Dropping Main Reinforcement Bars for Use as Support Bars, CRSI ETN-C-3-14**.

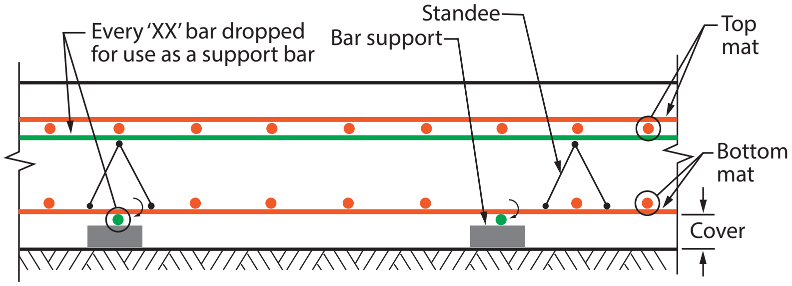
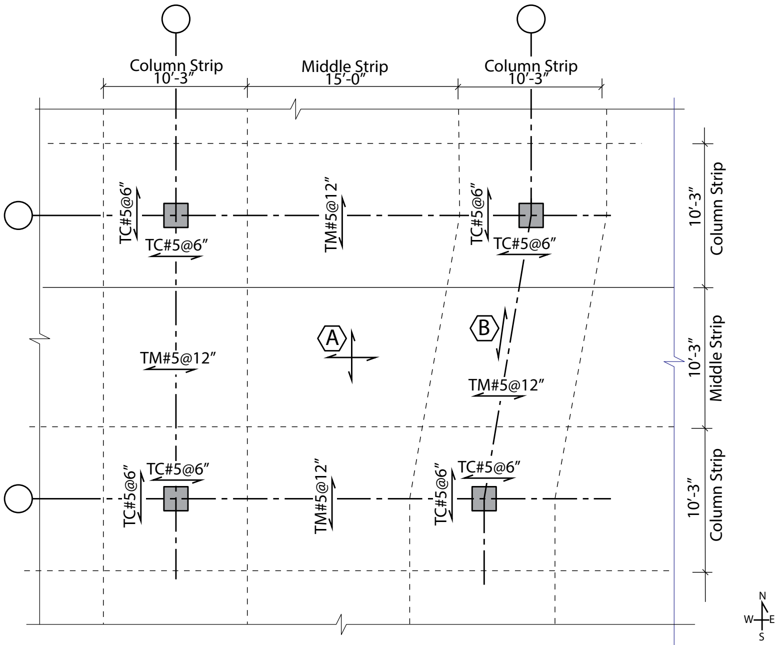


Fig. 2.7.17: Schematic section for a foundation with two mats of reinforcing bars. Support bars are used to ensure each layer of bars can be secured at the specified spacing and depth. In many markets, support bars are sourced by relocating (dropping) structural bars from the second layer in a bottom 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**."



Partial Slab Plan

Notes:
1) H = Slab thickness = 8"
2) ⟶ = Bar orientation
3) T = Top; B = Bottom;
C = Column strip; M = Middle strip
4) ⟨A⟩ Bottom bars #5 @ 12" EW Typ.
⟨B⟩ (2) BC#5 x 25'-0" @ 6" spacing centered on grid
5) Refer to Typical Column Strip and **Typical Top Bar Placement details**
6) 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. 2.7.18: 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).

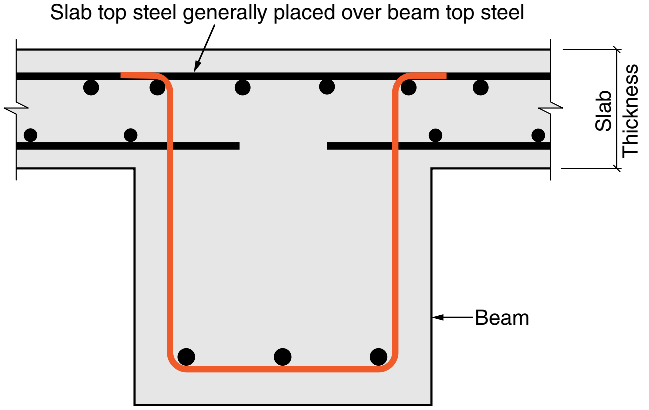


Fig. 2.7.19: When slabs are supported on beams, construction documents should include a detail showing the placement of slab top reinforcing passing over a beam.

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).

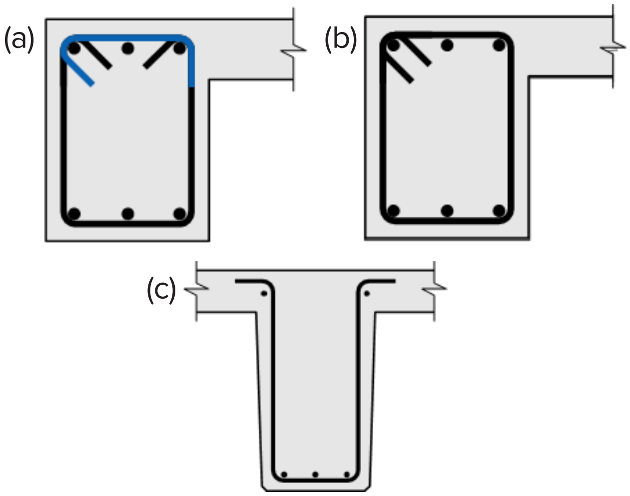


Fig. 2.7.21: Stirrup cage options: (a) two-piece stirrup; (b) one-piece stirrup, and (c) stirrup with out-turned hooks. (Image courtesy of CRSI.)

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).

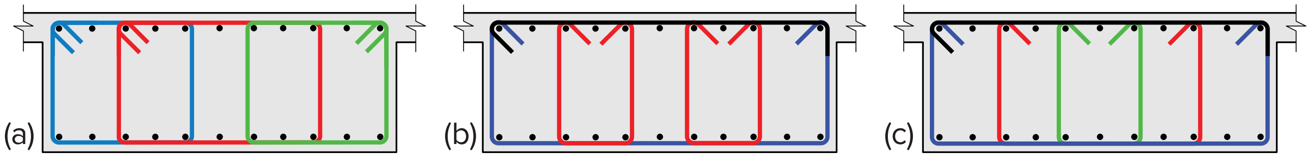


Fig. 2.7.23: Potential multi-leg stirrup configurations for a wide beam: (a) multiple closed stirrups across the width of a beam (not constructable); (b) an open-top perimeter stirrup with nested internal open-top stirrups; and (c) an open-top perimeter stirrup with two internal open-top stirrups. Detail (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**.)

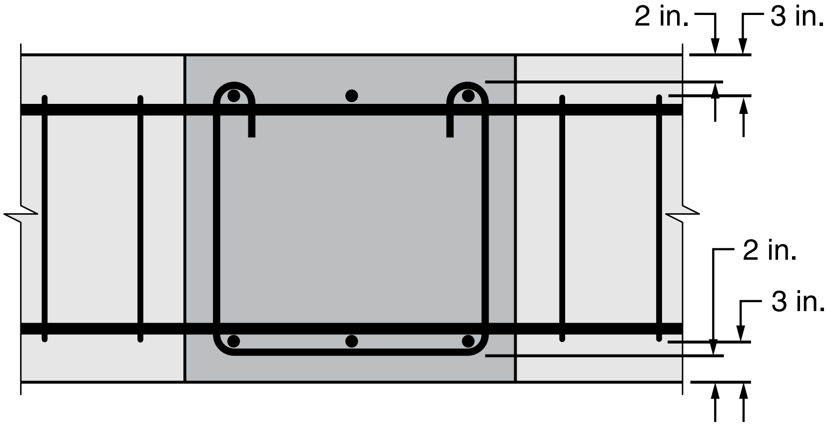


Fig. 2.7.25: The designer must establish the layering of reinforcing at intersecting beams. The addition of required cover values will add clarity to the construction documents.

(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.

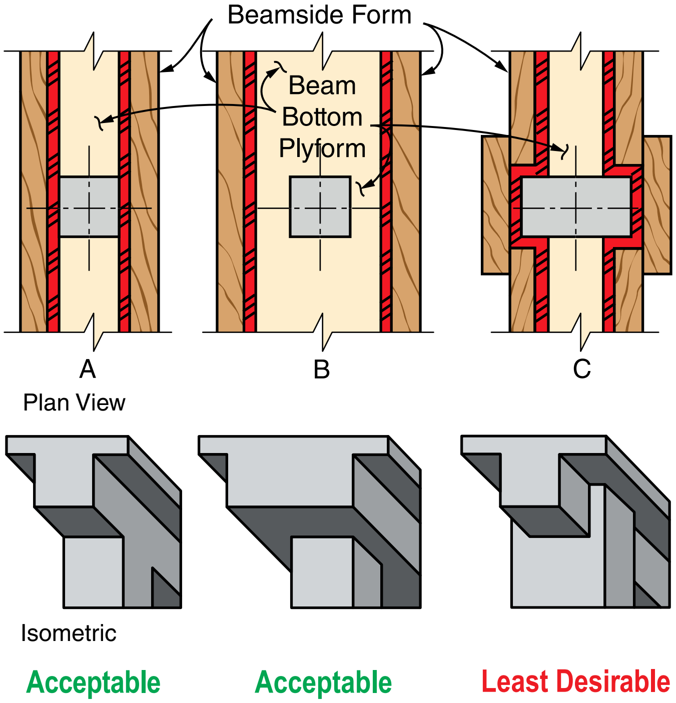


Fig. 2.7.26: The greatest economies in formwork construction are achieved when beams are at least as wide as columns. For parking structures built using steel beam formwork systems (Fig. 2.6.20), Plan View C is most desirable.

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

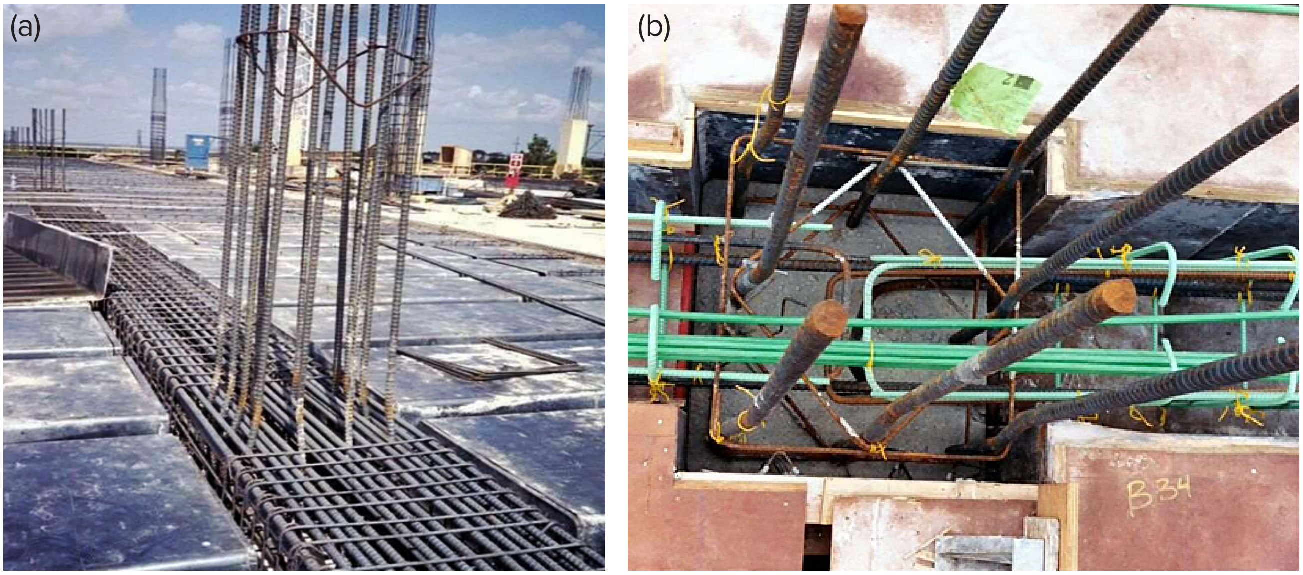


Fig. 2.7.27: Formwork and reinforcement at column-beam intersections: (a) a desirable beam width allows crews to route beam reinforcement around column bars; and (b) an undesirable beam width adds to formwork complexity and can result in interference between beam and column bars. (Images courtesy of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

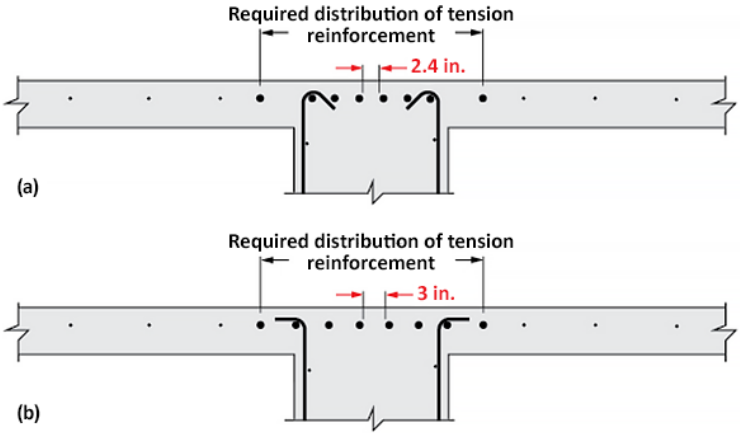


Fig. 2.7.28: ACI 318 Section 24.3.4 requires bonded tension reinforcement to be distributed within the lesser of the effective flange width b_f or a width equal to 10% of the clear span ℓ_n of the flexural member: (a) key features of Fig. E5.12 from the ***ACI Reinforced Concrete Design Handbook*** *illustrate 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.).*

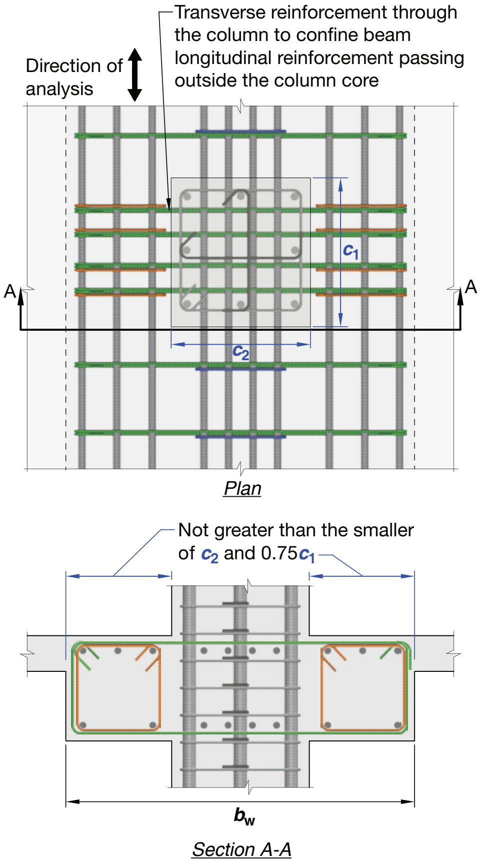
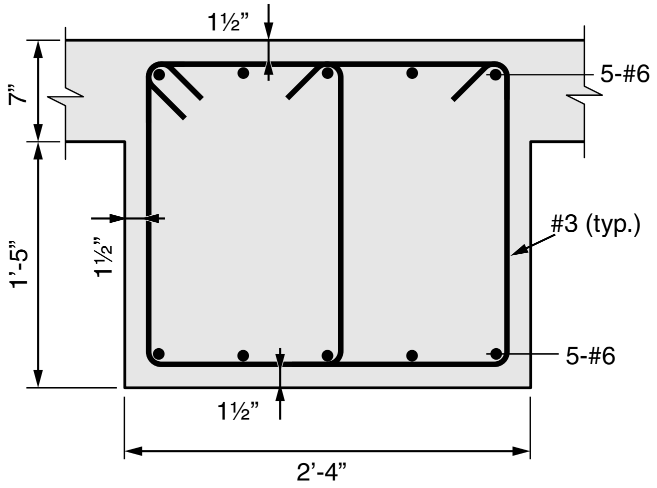


Fig. 2.7.29: Fig. R18.6.2 from ACI 318 illustrates the maximum effective width allowed for beams in special moment frames. This limit can conservatively be extended to beams where reinforcement congestion at beam-column intersections is a concern.

(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.”



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.)

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.

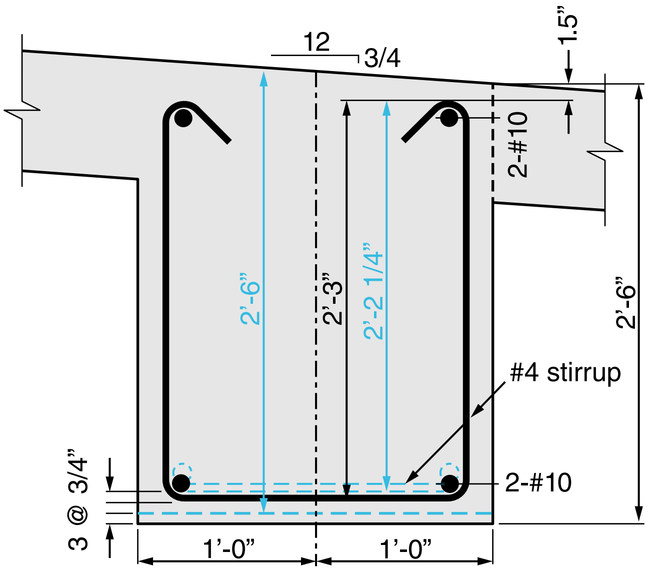


Fig. 2.7.31: In structures with sloping slabs, designers should specify that the beam depth is defined at its downhill side. (Image courtesy of CRSI.)

(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.

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.

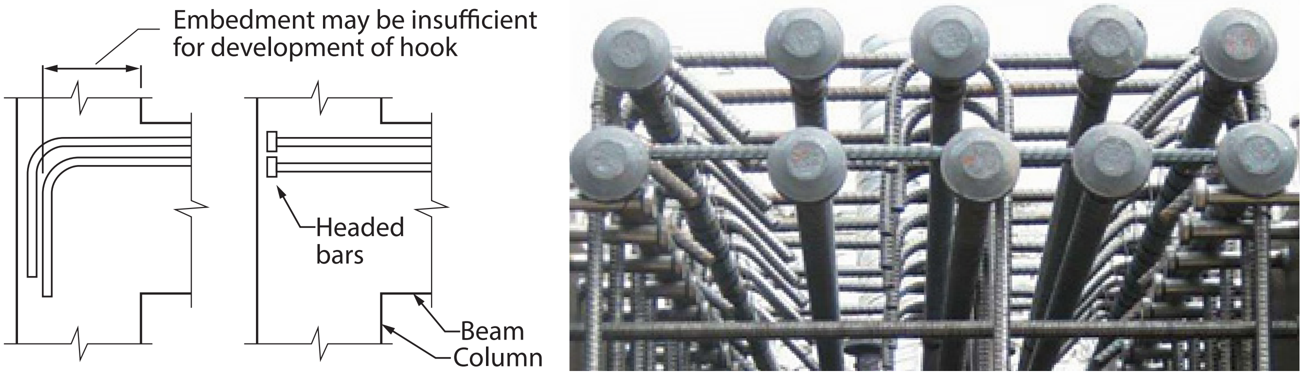


Fig. 2.7.32: Headed reinforcement can help avoid congestion and ensure adequate embedment to develop bars. (Detail source: STRUCTURE Magazine, May 2011, "Tips for Designing Constructible Concrete Structures, Part 2." Image courtesy of Headed Reinforcement Corp.)

(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).

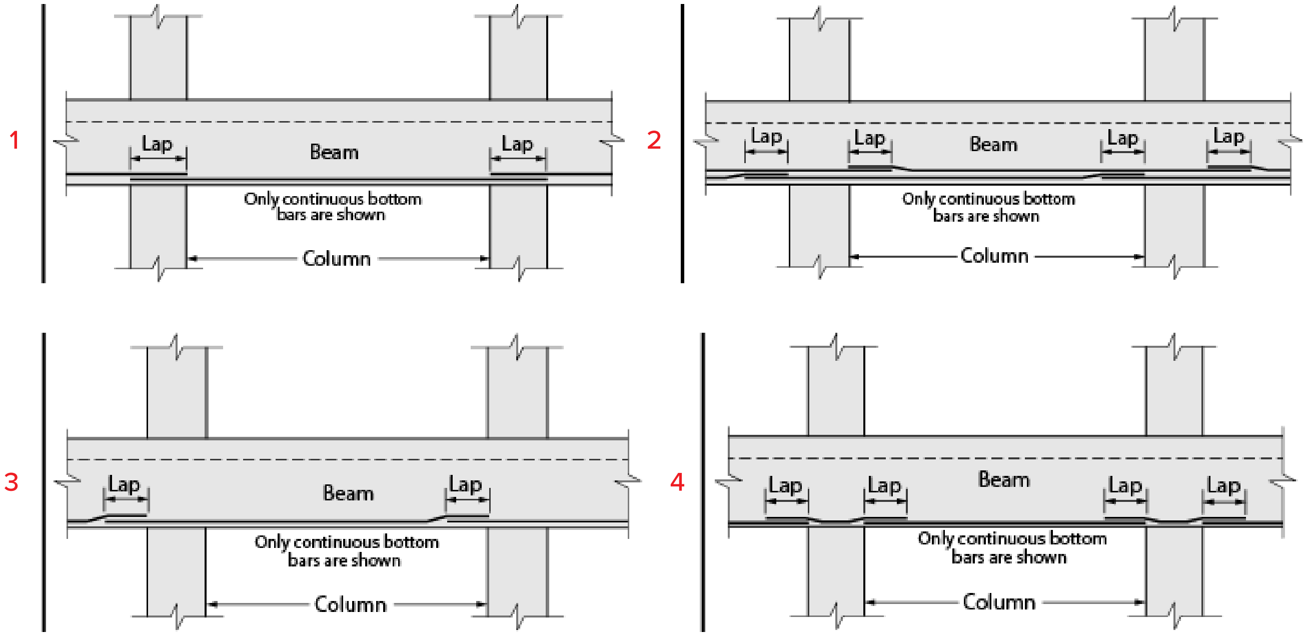
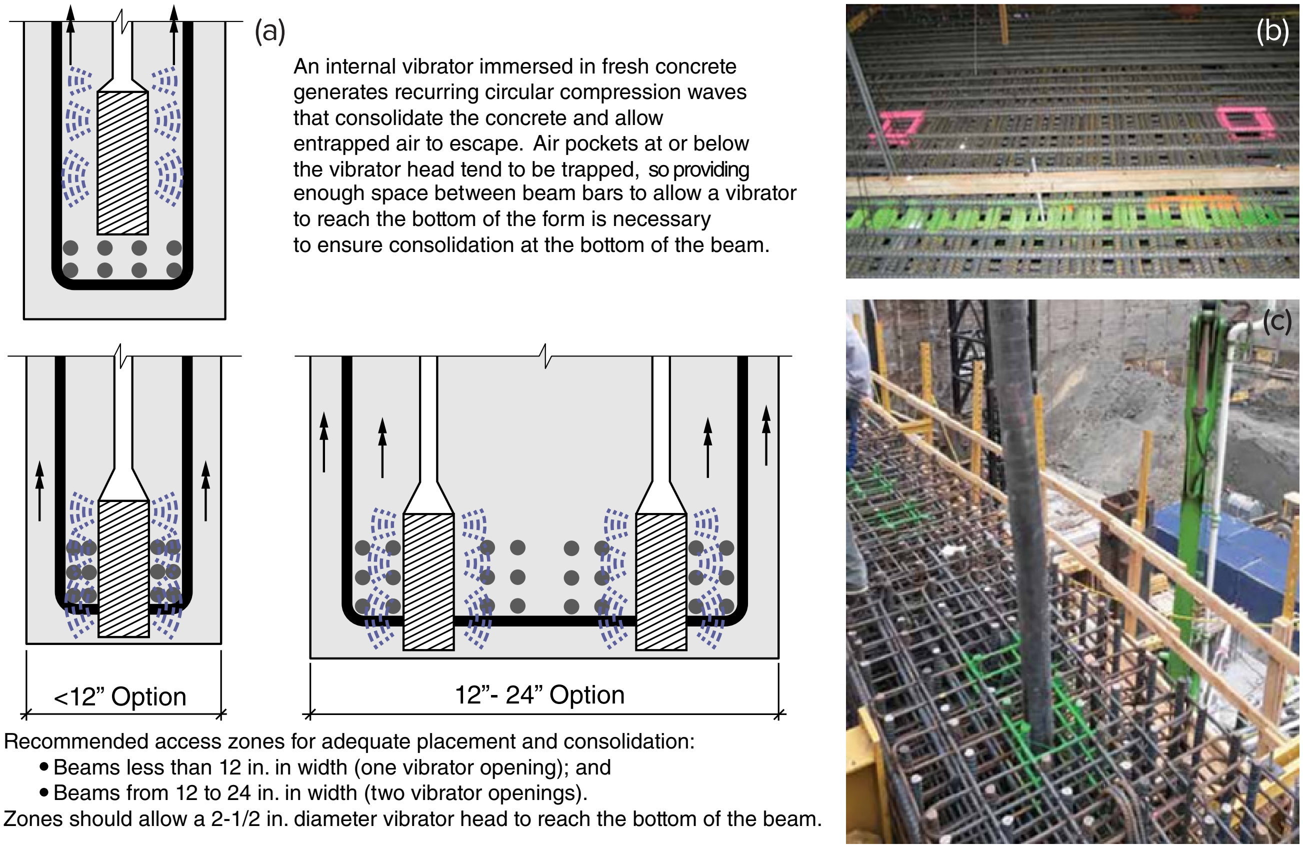


Fig. 2.7.33: Potential options for lap splices of continuous bottom reinforcing bars in beams. (Image courtesy of Concrete International*, December 2009, Beam-Column Joints, and CRSI Reinforcing Bars: Anchorages and Splices, 2022.)*

(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).



An internal vibrator immersed in fresh concrete generates recurring circular compression waves that consolidate the concrete and allow entrapped air to escape. Air pockets at or below the vibrator head tend to be trapped, so providing enough space between beam bars to allow a vibrator to reach the bottom of the form is necessary to ensure consolidation at the bottom of the beam.

Recommended access zones for adequate placement and consolidation:

- Beams less than 12 in. in width (one vibrator opening); and
- Beams from 12 to 24 in. in width (two vibrator openings).

Zones should allow a 2-1/2 in. diameter vibrator head to reach the bottom of the beam.

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.

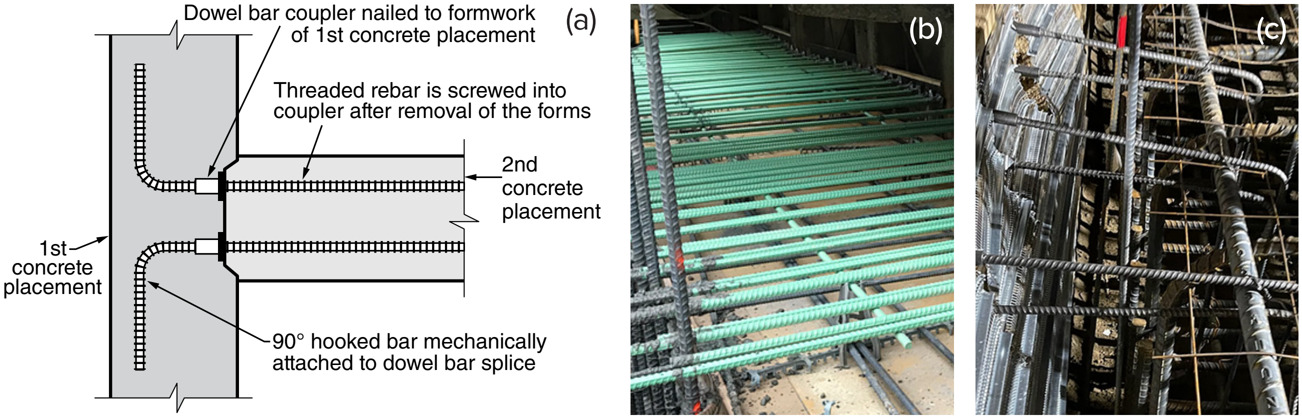


Fig. 2.7.35: Examples of dowel bar couplers at construction joints: (a) a suggested detail from "Design Guide for Economical Reinforced Concrete Structures"; (b) couplers attached to slab formwork (image courtesy of McHugh); and (c) couplers in a foundation construction joint incorporating a stay-in-place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

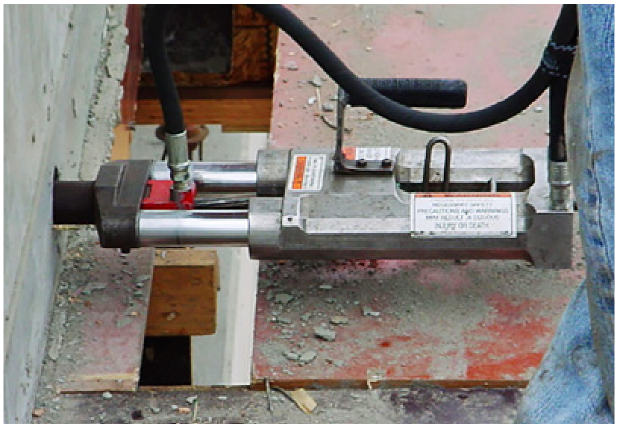


Fig. 2.7.36: The jacks used for tensioning PT cables require a 3 ft wide accessible zone. (Image courtesy of Post-Tensioning Institute.)

(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.

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.

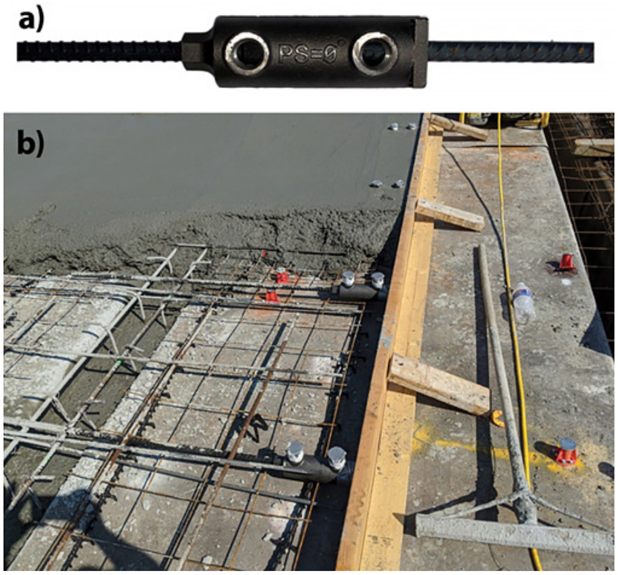


Figure 2.7.37: A reinforcement splice system capable of carrying shear across a joint without restraining shrinkage of adjacent bays: a) a coupler with bars; and (b) devices installed in the first pour side of a construction joint.

(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.

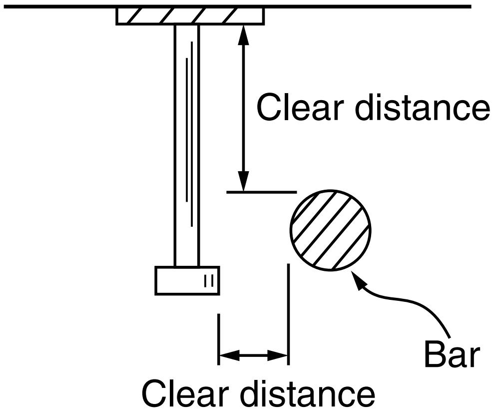


Fig. 2.7.38: Concrete flow can be impeded if the clearance between embedded items and the nearest reinforcing bar is too small. ACI 117-10 requires that the distance is at least the bar diameter, the largest aggregate size, or 1 in. (25 mm).

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.)

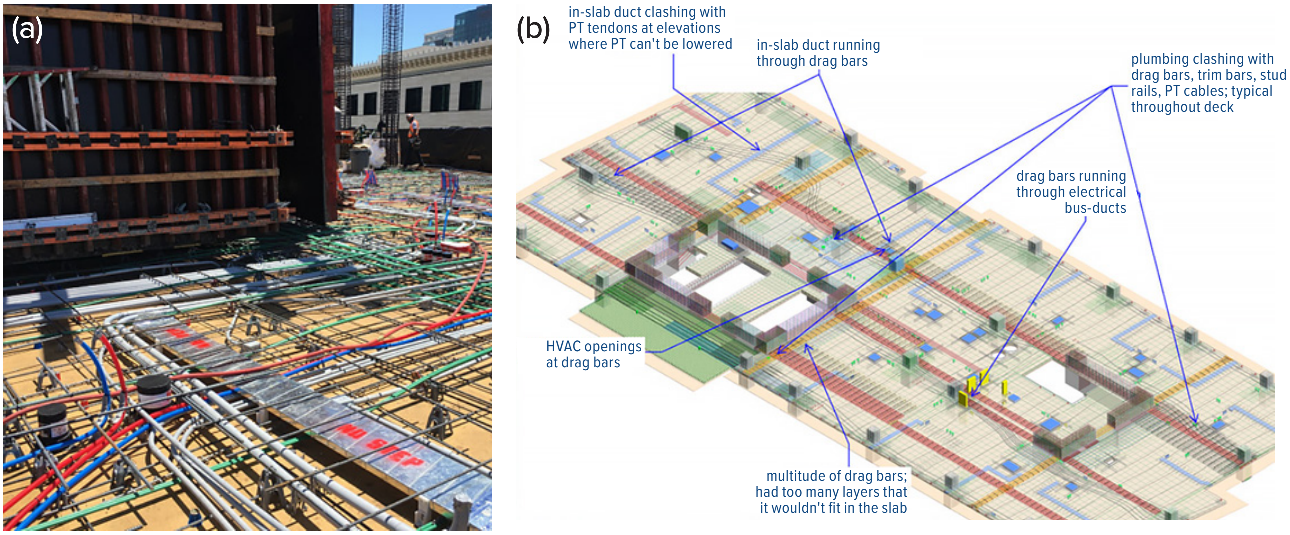


Fig. 2.7.40: Non-structural embeds can conflict with reinforcing bars and strands: (a) sleeves, conduit, and ducts can create major conflicts within elevated slabs; and (b) a 3-D model with all embedded structural and non-structural systems in a floor structure can help the design team avoid conflicts 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.

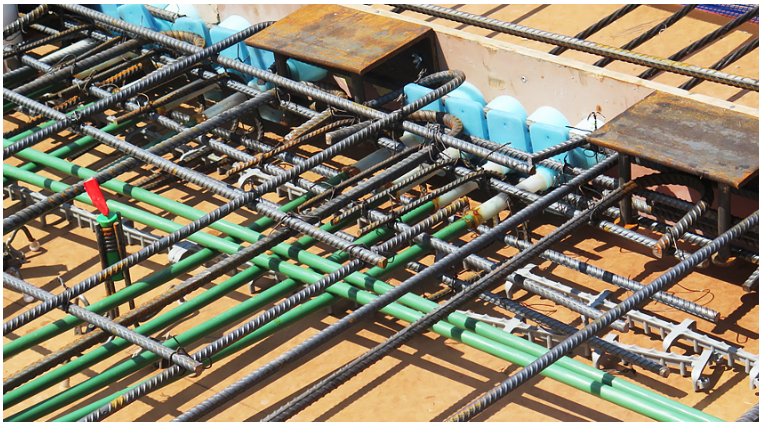


Fig. 2.7.43: Structural designers must coordinate embedded plates, anchors, reinforcing bars and PT systems. (Image courtesy of Ceco Concrete Construction.)

(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.

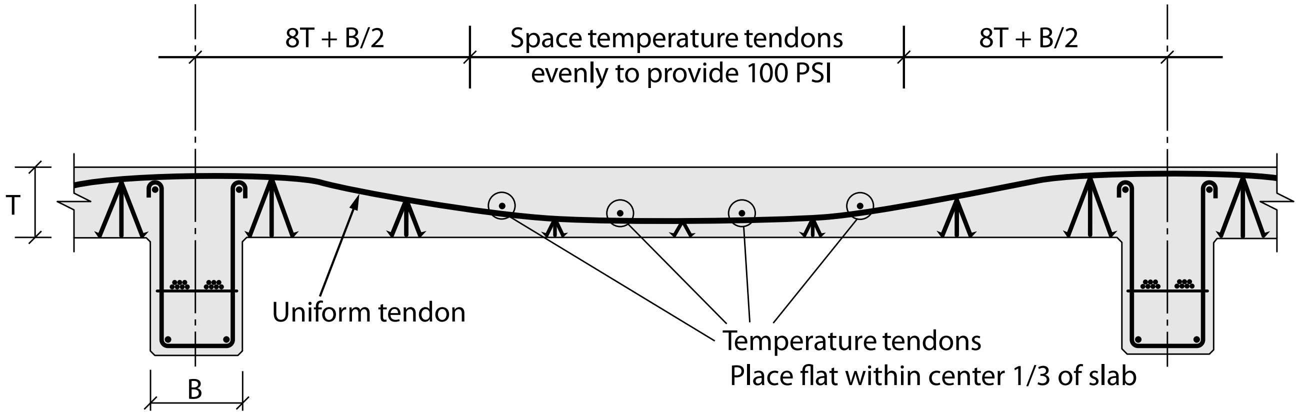


Fig. 2.7.44: While temperature strands may be supported directly on the uniform strands provided in one-way slabs, additional supports may be required to ensure the tendons are within the middle third of the slab. (Image courtesy of PTI).

(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).

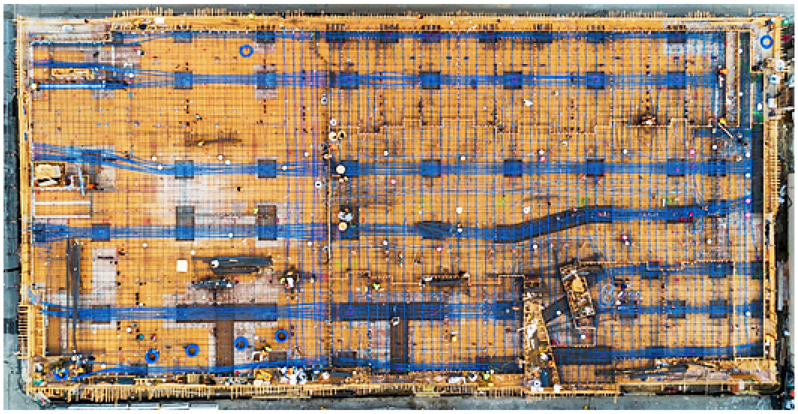


Fig. 2.7.46: An aerial view of a PT floor system shortly before concrete placement. (Images courtesy of PTI.)

(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**.

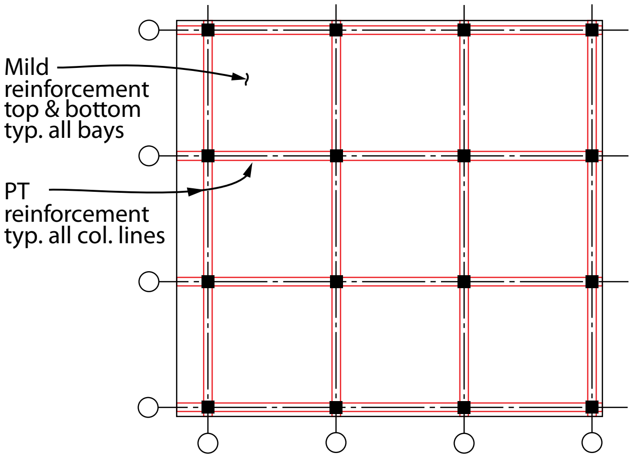


Fig. 2.7.47: A dual-banded PT system will allow large slab regions (reinforced with bars and/or steel fibers) that can be safely cored to accommodate future needs.

(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).

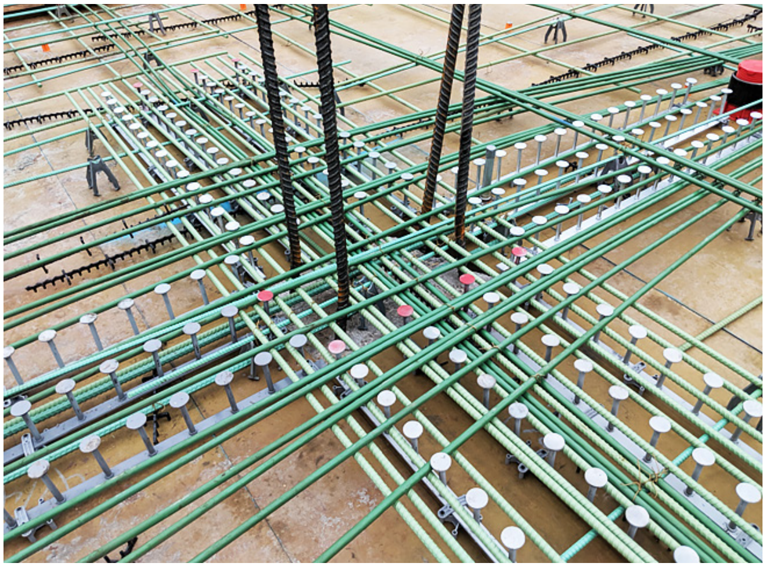


Fig. 2.7.48: Stud rails or double-headed studs can help designers avoid the need for drop panels. (Image courtesy of Amsysco.)

(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.)*

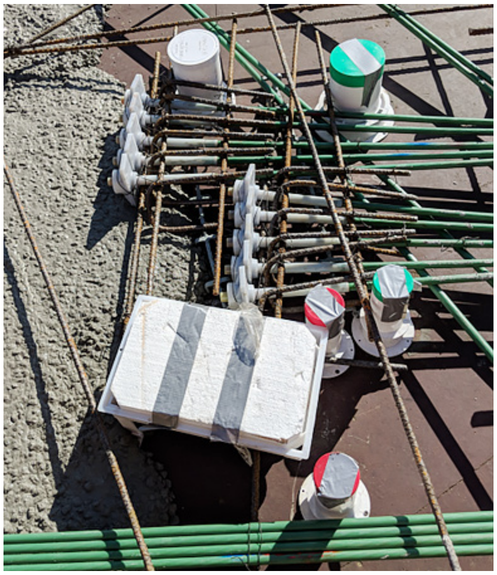


Fig. 2.7.50: PT anchors adjacent to Schedule 40 sleeves. (Image courtesy of Amsysco.)

(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!**

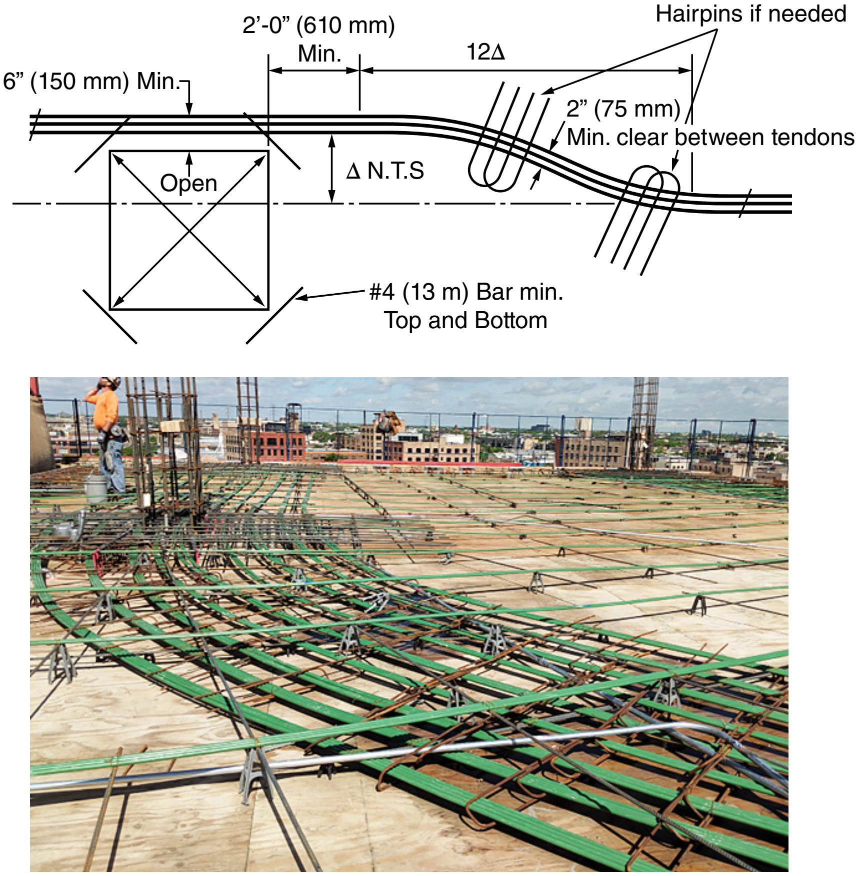


Fig. 2.7.51: Tendon sweeps should be anchored with hairpins if tendons are near slab openings and sleeves. (Diagram and image courtesy of Amsysco.)

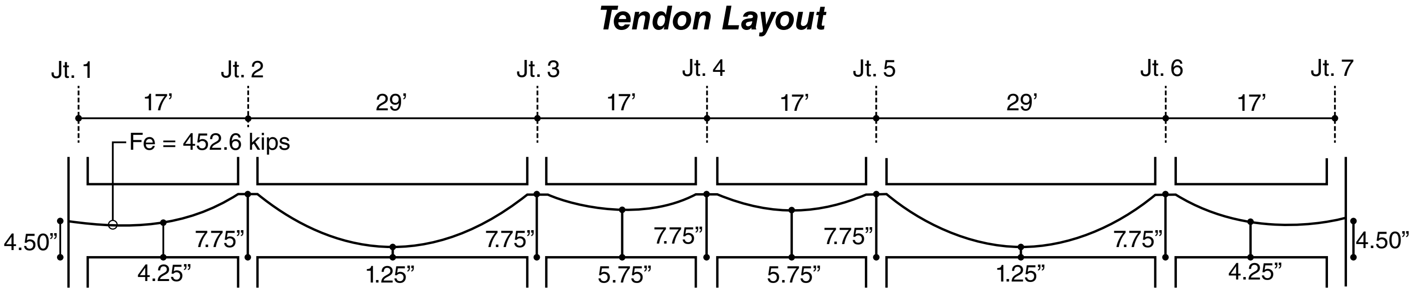


Fig. 2.7.52: Draped strands can provide constructability solutions for transfer girders. Define strand drapes by providing dimensions from the soffit to the strand center of gravity at each support and at midspan of each span. (Image courtesy of PTI.)

(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 P-T Anchors in Shear Walls**." Figure 2.7.53 provides a detail from that article as well as a photo of PT installation at walls.

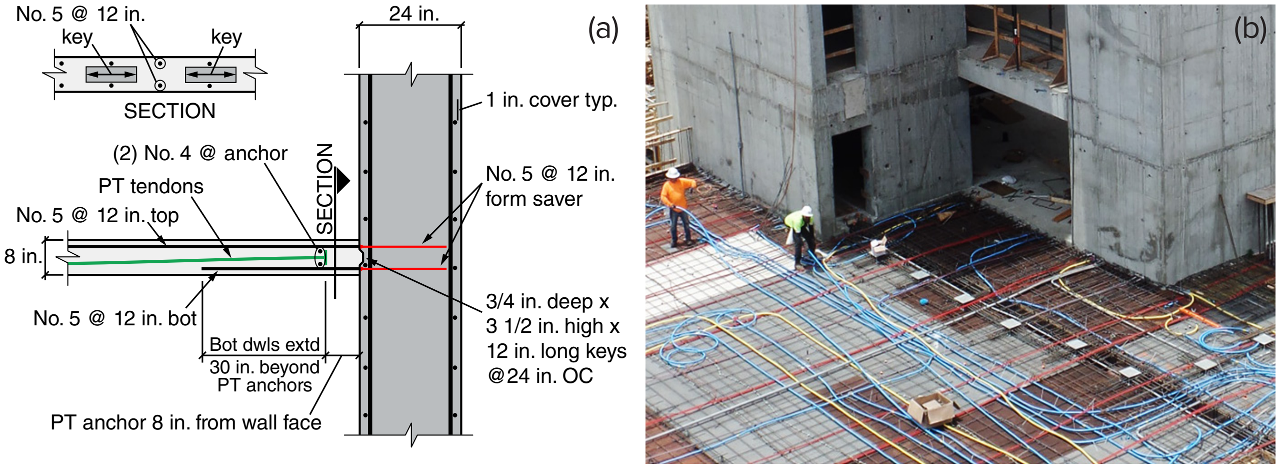


Fig. 2.7.53: A highly constructable option for strand anchorage is to place dead-end anchors near the wall face: (a) a detail from the referenced article; and (b) use of such details allows walls to be constructed ahead of floor structures. (Image courtesy of Ceco Concrete Construction.)

(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.

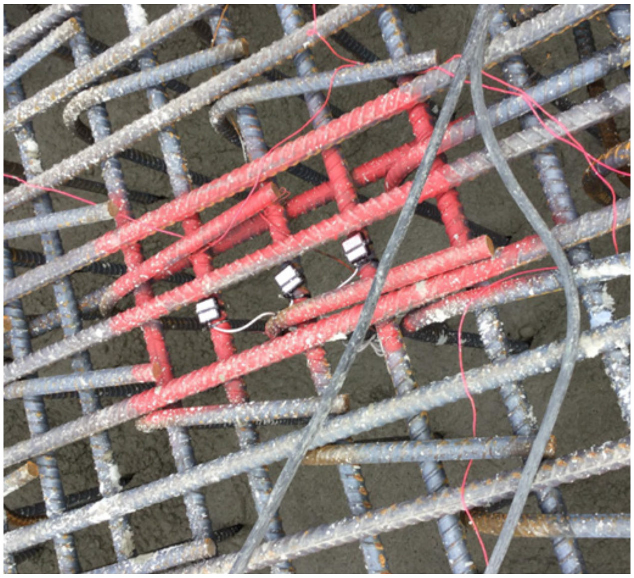


Fig. 2.7.54: Temperature sensors can be used to monitor concrete curing and estimate the in-place concrete strength. (Image courtesy of Conco.)

(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.

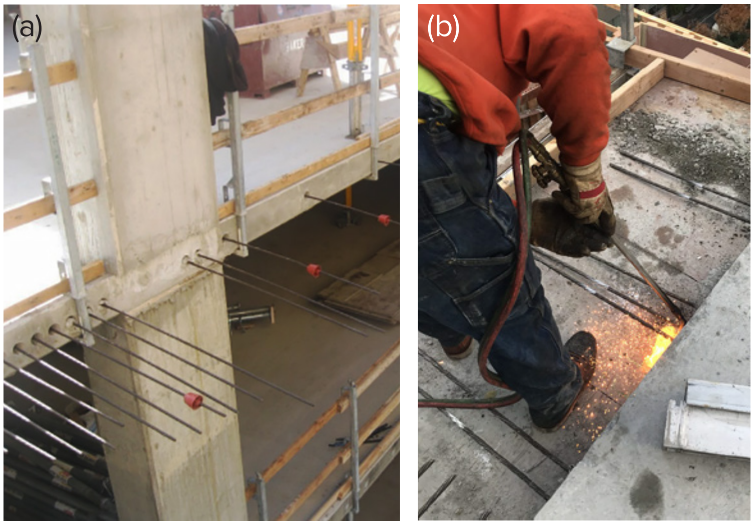


Fig. 2.7.55: PT strand tails must be cut to allow protective systems to be installed at the anchors: (a) strand tails extending from a PT slab (image courtesy of PTI); and (b) a worker cuts a tail using an acetylene torch (image courtesy of Conco.)

2.8 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**.

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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.

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