CHAPTER

three

DESIGN CONSIDERATIONS

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Precast concrete's high level of quality fabrication and its array of benefits help architects meet a variety of design challenges. These goals can range from projecting the appropriate image today to maintaining that appearance and retaining all functional activities for decades into the future. Maximizing the performance of the material requires an understanding of its capabilities and limitations related to each goal.

The aesthetic options available with architectural precast concrete components, especially wall panels, are considerable. They can mimic a wide variety of other masonry alternatives, including brick and stone, providing many options for duplicating existing architectural styles used with surrounding buildings. This holds true whether the styles are historic or contemporary.

In many cases, architectural finishes also can be provided for structural precast components, combining functions and saving material cost and construction time. Precast components also mesh well with other materials, including curtain walls, and they can accommodate any required penetrations. Special considerations will aid the installation of mechanical systems and vapor barriers, all of which can be accommodated easily.

Precast concrete's economy aids owners and designers in meeting their budgetary needs and helps make funds available that are typically needed for design consideration for other key elements. Its economy not only reduces the immediate in-ground cost but also continues to save operating expenses over the life of the building through extended durability and lower maintenance costs. Precast concrete can also aid in meeting sustainability goals set by the owner, including certification standards set by the Leadership in Energy & Environmental Design (LEED) program instituted by the U.S. Green Building Council (USGBC).

A variety of additional design challenges, such as maximizing fire resistance, heightening acoustic control, and providing safety provisions, can all be met by designing precast concrete components to the appropriate specifications. Architects who work closely with their local precaster during the design phase and throughout the development of the contract documents can ensure their projects make efficient use of the material's wide range of capabilities to provide optimum value and quality while minimizing construction cost.

CHAPTER THREE a.

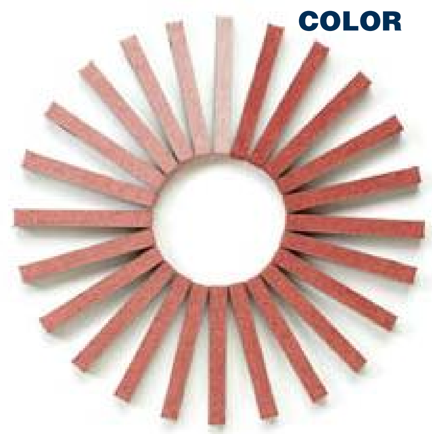
Aesthetics

Precast concrete is a visually rich material that allows the architect to be innovative and attain design objectives that cannot be achieved with any other material. The architect's selection of color, form, and texture is critical to the aesthetic appearance of architectural precast concrete components. The choice of appropriate aggregates and textures, combined with well-conceived production and erection details, can achieve a wide variety of design objectives.

Design flexibility is possible in both color and texture of precast concrete by varying aggregate and matrix color, size of aggregate, finish processes, and depth of aggregarate exposure. Combining color with texture accentuates the natural beauty of aggregates.

With the vast array of colors, textures, and finishes available, designers can use precast concrete to achieve almost any desired effect.

COLOR



These swatches illustrate the different shades that can be created in architectural precast using a single pigment at many different concentrations. They represent addition rates of red pigment from 1/4% to 7% in a white cement base.

Color is a relative value, not an absolute and unvarying tone. It is affected by light, shadow, density, time, and other surrounding or nearby colors. Color selection should be made under lighting conditions similar to those under which the precast concrete will be used, such as the strong light and shadows of natural daylight. Surface texture influences color. The building's appearance is a function of the architect's use of light, shadow, texture, and color.

Cement combined with a coloring agent exerts the primary color influence on a smooth finish, because it coats the exposed concrete surface. As the concrete surface is progressively removed and aggregates are exposed, the panel color increasingly exhibits the fine and then the coarse aggregate colors. The color of the cement always has an effect on the general tone of the panel. Cement may be gray, white, or a mixture. All cements have inherent color and shading differences, depending on their source.

Pigments and pigmented admixtures are often added to the cement matrix to obtain colors that cannot be created through combinations of cement and fine aggregate alone. White portland cement will produce cleaner, brighter colors and where color is important should be used in preference to gray cement with pigments, especially for the light pastels such as buff, cream, pink, rose, and ivory.

Fine aggregates have a major effect on the color of white and light buff-colored concrete and can add color tones when the surface is given a shallow profile to increase the aggregate's exposure. Coarse aggregate colors become dominant as the surface of the concrete is removed to obtain a medium or deep aggregate exposure profile.

Some finishing processes change the appearance of aggregates. Sandblasting will give the aggregates a matte finish, while acid-etching may increase their brightness. Exposure by retardation of the surface cement normally leaves the aggregates unchanged.

Maintaining consistency of color throughout the production run requires attention to detail and proper specification. Eight key factors should be closely controlled when color consistency is critical:

1. Type and color of cement.

2. The quality and quantity of the coloring agent.

3. Proper batching and mixing techniques and the coloring agent's effect on the concrete's workability.

4. Quality (that is, freedom from impurities) of the fine and coarse aggregates.

5. Uniform quantities and gradation of the fine materials (capable of passing through a No. 50 sieve, including the cement) in the concrete mix.

6. Careful attention to curing and uniform duplication of curing cycles.

7. Constant water-cement ratio in the mix.

8. Consideration of the factors that can contribute to efflorescence. Its appearance on the concrete's surface can mask the true color and give the appearance of color fading. Should efflorescence occur, it can be washed off when its appearance on the panel is noticed.

The ease of obtaining uniformity in color is directly related to the ingredients supplying the color. Optimum uniformity is obtained by using white cement. Extreme color differences between aggregates and matrix should be avoided.

Color should be judged from a full-sized sample that has the proper cement matrix and has been finished in accordance with planned production techniques (see Reference 1).

TEXTURES

The Anadarko Tower located in The Woodlands, Tex., was clad with light and medium sandblast, textured precast panels composed of a single-face mix design. Some of the panels were supplemented with thermal finished Luna Pearl granite insets. The mix was composed of 100 percent white portland cement, coarse aggregates, fine aggregates, and pigment. Photo: Gensler.

Texture allows the naturalness of the concrete ingredients to be expressed, provides some scale to the mass of the building, expresses the creative aspect of the concrete, and improves the weathering characteristics of the element surface. A variety of textures can be achieved, ranging from a honed or polished surface to a deeply exposed, 3-in.-diameter, uncrushed aggregate surface.

The final appearance of any precast concrete finish will depend on the selection of aggregate color and size, matrix color, shape details or form, surface finish, and depth of aggregate exposure. Four major factors should be considered in choosing a texture:

1. The area of the surface. Coarse textures are difficult to use on small areas. Dividing large, flat areas by means of rustications tends to deemphasize any variations.

2. The viewing distance. From a greater distance, different textures will provide different tonal values. Determining the normal viewing distance in the final use will impact which textures and sizes of aggregates should be used.

3. The orientation of the building's wall elevation. The siting determines the amount and the direction of light on the surface and how the panel will weather.

4. Aggregate particle shape and surface characteristics. Both the shape and surface characteristics determine how the surface will weather and reflect light (see Reference 2.).

There are three key levels of exposure that are used in creating a finished appearance:

1. Light exposure involves removing only the surface skin of cement and sand. This sufficiently exposes the tips of the closest coarse aggregate.

2. Medium exposure requires further removal of cement and sand to cause the coarse aggregates to appear approximately equal in area to the matrix.

3. Deep exposure requires cement and sand to be removed from the surface so the coarse aggregates become the major surface feature (see Reference 3.).

FINISHES

The single concrete mix shown here has three different finishes. From left to right, they are acid etch, sandblast, and retarded. This multiple-finish technique offers an economical, yet effective, way to heighten aesthetic interest.

A wide range of surface finishes are available, achieved through a variety of processes. Before a specific finish is specified, sample panels should be created to ensure the finish achieves the desired aesthetic and functional goals.

Samples may be provided by competing producers initially in small, 12-in. squares. The selected producer should then provide three 4 ft^2 or 5 ft^2 samples to determine color range. The range of acceptable variations in color, texture, and uniformity should be determined when these mockup units are approved. Full-scale mockups should be specified by the architect to arrive at a final approval of the desired design (see Reference 4).

The most common types of finishes available include:

388 Market Street building in San Francisco, Calif., is clad with 1 1/4 in. (3 cm) granite anchored to precast concrete. Architect: Skidmore, Owings & Merrill; Photo: Skidmore, Owings & Merrill San Francisco.

- **Smooth as-cast finishes** show the natural look of the concrete without trying to simulate any other building product. Fine surface details and sharp arrises can be achieved. When a high level of color uniformity is required, this finish is strongly discouraged (see Reference 5).

- **Exposed-aggregate finishes**, via chemical retarders or water washing, are achieved with a non-abrasive process that effectively brings out the full color, texture, and beauty of the coarse aggregate. The aggregate is not damaged or changed by this exposure method (see Reference 6).

- **Formliners** provide an almost unlimited variety of patterns, shapes, and surface textures. The concrete is cast against liners made of a range of materials, including wood, steel, plaster, elastomeric, plastic, or foam plastic (see Reference 7).

- **Sand or abrasive blasting** provides all three degrees of exposure noted above. This process is suitable for exposure of either large or small aggregates. Uniformity is directly proportional to the depth of material removal (see Reference 8).

Examples of light, medium, and heavy sandblast textures.

- **Acid etching** dissolves the surface cement paste to reveal the sand, with only a small percentage of coarse aggregate being visible. It is most commonly used for light or light-to-medium exposure (see Reference 9).

Examples of light, medium, and heavy acid-washed textures.

- **Tooling, usually called bushhammering**, mechanically spalls or chips the concrete surface using any of a number of hand or power tools, producing an abraded aggregate texture. Each tool produces a distinctive surface effect and a unique shade of concrete color (see Reference 10).

- **Hammered-rib or fractured-fin designs** are created by casting ribs onto the surface of the panels and then using a hammer or bushhammer tool to randomly break the ribs and expose the aggregate. The effect is a bold, deeply textured surface (see Reference 11).

- **Sand embedment** creates a bold and massive appearance for the panel, using 1- to 8-in.-diameter stones or flagstones. The stones typically are placed in a sand bed at the bottom of the mold, and finishing reveals the stone face, resulting in the appearance of a mortar joint (see Reference 12).

- **Honing or polished finishes** are achieved by grinding the surface to produce smooth, exposed-aggregate appearances. Polished, exposed-aggregate concrete finishes compare favorably with polished natural stone façades, such as granite (see Reference 13).

- **Painting or staining** is used purely for decorative purposes, due to the high-strength, durable nature of precast concrete panels. There is a vast difference in paint types, brands, prices, and performance, and knowledge of composition and performance standards is necessary to obtain a satisfactory result. In some cases, the precast concrete surface can be so smooth that it makes adhesion difficult to obtain, so a decision on painting should be made prior to casting if possible (see Reference 14).

Panels on the Shriners Hospital for Crippled Children, Sacramento, Calif., are 6 in. thick and have a horizontal band of 1 1/4 in. granite attached with one anchor per 2 ft^2. Architects: Odell Associates; and Associate Architect: HDR.

Multiple mixtures and textures in the same unit provide design flexibility. Color and texture variations can be obtained by manipulating aggregates and matrix colors, size of aggregates, formliners, finishing processes, and depth of exposure. A rustrication feature needs to be detailed to separate the different colors and/or finishes.

Combinations of various finishes on the same unit depend on the shape of the unit. Some finishes, such as acid etching, can't be easily applied to only one portion of a unit. The combination of a polished or honed surface and acid etching provides a surface that exposes a very high percentage of aggregate (see Reference 15).

FACING PRODUCTS AND ARCHITECTURAL TRIM UNITS

Arizona red sandstone, 1 1/4 in. to 1 3/4 in. thick, was anchored to 4-in.-thick concrete panels for the Sacramento Municipal Utility District's Customer Service Center, Sacramento, Calif.; Architect: Williams + Paddon Architects & Planners/Inc.

Clay product-faced precast concrete panels combine the pleasing visual appearance of traditional masonry products with the strength, versatility, and economy of precast concrete. Clay products that can be cast integrally with precast concrete panels include brick, ceramic tile, and terra cotta. The clay product can cover the entire exposed-panel surface or only a portion, serving as an accent band or contrasting section. Marble, glass, and ceramic mosaics can also be cast integrally (which is preferred) or applied to the hardened concrete (see Reference 16).

The combination of precast concrete and clay products has several advantages over site-laid-up masonry. By using precast concrete panelized construction, the need for on-site scaffolding and significant on-site labor is eliminated, which can be a significant cost savings over masonry construction.

Structural design, fabrication, handling, and erection aspects of clay product-faced precast concrete units are addressed similarly to those for other precast concrete wall panels except that special consideration must be given to the dimensional layout of the clay product and its embedment in the concrete. The physical properties of the clay products must be compatible with the properties of the concrete backup. The most significant property is the coefficient of thermal expansion, which causes volume change. It is best to select material with similar coefficients of expansion along with tight dimensional tolerances.

Reinforcement of the precast concrete backup should follow recommendations for precast concrete wall panels relative to design, cover, and placement. Uniform and even coursing without cutting any units vertically or horizontally except as necessary for running bond allow for economical production. To achieve this thin brick conforming to the PCI standard for embedded brick should be specified (see Reference 17).

Natural stone has been widely used in building construction due to its strength, durability, aesthetic effect, availability, and inherent low-maintenance costs. Stone veneers for precast concrete facings are usually thinner than those used for conventionally set stone, with the maximum size generally determined by the stone strength.

When purchasing stone, a qualified individual should be appointed to be responsible for coordination, which includes delivery and scheduling responsibility and ensuring color uniformity (see Reference 18).

Architectural trim units (cast stone) are manufactured to simulate natural cut stone. They are used in masonry work mostly as ornamentation and architectural trim for stone bands, sills, lintels, copings, balustrades, and door and window trimming. They replace natural cut stone or terracotta in these applications (see Reference 19).

One-in.-thick brick cladding on 5-in.-thick concrete panels was used on the first three floors of the Sacramento County System and Data Processing Building in Sacramento, Calif. Terracotta medallions were placed on spandrels and column covers. Architect: HDR Architecture Inc. formerly Ehrlich-Rominger; Photos: HDR Architecture Inc.

MATCHING PRECAST WITH CAST-IN-PLACE CONCRETE

Architectural precast panels for the new wing of the Joslyn Art Museum, Omaha, Neb., are clad in Georgia marble to match the original stone building constructed in 1931. Labor and material cost were reduced using this system compared to traditional stone cladding systems. Architect: Henningson, Durham & Richardson Inc.

Precast concrete panels are often used in conjunction with architectural cast-in-place concrete. Matching these finishes to create a monolithic look must be planned before construction starts to allow adjustment of mix design, placement technique, methods of consolidation, and finishing procedures. Samples and full-scale mockups should be prepared for both the precast and cast-in-place panels, and differences should be resolved prior to finalizing either finish.

When both products will be used in the same plane, the cast-in-place tolerances must be strictly enforced. Differences in curing methods between the two techniques, even with identical mixes, may cause color variation in the finish, particularly if the precast concrete uses accelerated, high-temperature curing. Different weathering patterns may result in dissimilar appearances due to different concrete densities (see Reference 20).

INTERIOR FINISHES

Architectural precast concrete panels both inside and out bring drama and quality to the recent 3 million-ft^2 expansion of McCormick Place in Chicago, Ill. Photo: Brian Gassel/TVS&Assoc.

The interior side of architectural precast concrete panels can also be given an aesthetic finish, eliminating the need to provide an additional finished wall, saving materials, time, and cost. Exposed interior surfaces should have finishes that are realistic in terms of exposure, production techniques, configuration of the precast concrete units, and quality requirements.

A variety of finishes for the back of a precast concrete panel can be provided. They include screed, light broom, float, trowel, stippled, or waterwashed or retarded exposed-aggregate finishes or sandblast finish. If the finish is to be painted, a stippled concrete finish normally will be the most economical. A trowelled finish is the most common interior finish, but it frequently darkens the surface in uneven patterns.

The treatment of joints and connections with regard to interior-finish requirements should be considered if panels are to remain exposed. Load-supporting connections at the top and bottom of the panel should be hidden above the ceiling panels and below the floor level, respectively. If they are exposed, they should be recessed (see Reference 21).

ACCEPTABILITY OF APPEARANCE

Contract documents should spell out who the accepting authority for the panel color, finish, and texture will be. This is typically the owner, architect, general contractor, or site inspector. One person must have final authority on all issues of appearance. Determing acceptable uniformity of color, finish, and texture is by visual examination, and is generally a matter of subjective, individual judgment and interpretation. The acceptable variations should be determined at the time the visual mockups or initial production units are approved. Suitable criteria for acceptability require that the finished concrete face surface should have no readily visible imperfections other than minimal color and texture variations from the approved samples or evidence of repairs when viewed in good, typical daylight illumination with the unaided, naked eye at a 20 ft or greater viewing distance.

Built in 1906, the architectural landmark 88 Kearney St. in San Francisco had its terra cotta removed and reassembled on precast panels for an all-new structure of taller height. Architect: Skidmore, Owings & Merrill; Photo: Skidmore, Owings & Merrill.

Appearance of the surface should not be evaluated when light is illuminating the surface from an extreme angle, as this tends to accentuate minor surface irregularities due to shadowing.

Building façades may be oriented such that sunlight just grazes the surface at a particular time of day. This causes otherwise imperceptible ripples, projections, and misalignments on the surace to cast long shadows and be grossly exaggerated in appearance. The shadows may last briefly. The actual time at which they appear varies with the season for a particular wall. Precast concrete, like any building surface, is subject to manufacturing and alignment tolerance so that the effect cannot be avoided.

Units should be assessed for appearance during dry weather. In climates with intermittent dry and wet conditions, drying-out periods may produce temporary mottled appearances.

Minor surface abnormalities and blemishes will occur on occasion, and precasters can adequately repair minor problems quickly. There are key finish defects and/or problems that are considered unacceptable in the fabrication of high-quality, PCI-certified architectural precast concrete (see Reference 22). These should be addressed as soon as they appear to ensure that the condition that caused the defects is corrected early in the production sequence. The unacceptable conditions for architectural concrete are:

- Ragged or irregular edges.
- Excessive air voids ("bug holes" or "blow holes") in the exposed surface.
- Adjacent flat and return surfaces with noticeable differences in texture and/or color from the approved samples or mockups.
- Casting and/or aggregate segregation lines evident from different concrete placement lifts and consolidation.
- Visible form joints or irregular surfaces of or larger than those acceptable in the approved samples or mockups.
- Rust stains on exposed surfaces.
- Excessive variation of texture and/or color from the approved samples, within the unit, or compared with adjacent units.
- Blocking stains or acid stains evident on panel surface.
- Areas of backup concrete bleeding through the face concrete.
- Foreign material embedded in the face.
- Repairs visible at 20 ft or greater viewing distance.

The flagship retail store for Tommy Hilfiger used 180 GFRC panels and decorative architectural details to create a striking façade on the corner of Santa Monica Boulevard and Rodeo Drive in Beverly Hills, Calif. Architect: Allan Greenberg, Architect Washington, D.C. Photo: Derek Rath.

- Reinforcement shadow lines.
- Visible cracks at a 20 ft or greater viewing distance.

Precast concrete generally undergoes far less cracking than cast-in-place concrete. This resistance results in part from the high compressive and tensile strength of the precast concrete. A certain amount of cracking may occur without having any detrimental effect on the structural capacity of the member, and it is impractical to impose specifications that prohibit cracking. Cracks can be unsightly and create potential locations for concrete deterioration, so any cracking should be avoided and those cracks that do appear should be inspected to determine acceptability. Cracks may be repaired and effectively sealed by pressure-injecting a low-viscosity epoxy.

The best methods to minimize cracks are to provide proper reinforcement locations, prestressing when appropriate, and proper handling. Whether cracks are acceptable will depend on an evaluation of the cause of the cracking and the service condition requirements, structural significance, and aesthetics.

Erected panels not complying with the contract documents may require additional work. Trial repairs should be applied to the project mockup or small sample panels and allowed to cure, followed by a normal drying period. Acceptability criteria for repairs should be agreed on at an early stage of the project. A certain amount of repair is to be expected as a routine procedure. Repair and patching of precast concrete is an art that requires expert craftsmanship and careful selection and mixing of materials (see Reference 23).

Repairs should be done only when conditions exist that ensure the repaired area will conform to the balance of the work's appearance, structural adequacy, and durability. Slight initial color variations can be expected between the repaired area and the original surface due to the different age and curing conditions of the repair. Time will tend to blend the repair into the rest of the component to make it less noticeable.

GFRC with horizontal striations relate the Pleasanton Corporate Campus buildings to the hills, creating the texture and shadow pattern HOK/SF Inc. Architects were looking for. Photo: HOK/SF Inc.

GLASS FIBER–REINFORCED CONCRETE (GFRC)

Glass fiber–reinforced concrete, commonly known as GFRC, is a composite concrete product fabricated by many precast concrete manufacturers. It consists of a portland-cement-based composite that is reinforced with an absolute, minimum of 4% by weight of alkali-resistant glass fibers to total mix, which are randomly dispersed through the material. The fibers serve as reinforcement to enhance the concrete's flexural, tensile, and impact strength.

The manufacture of GFRC products requires a greater degree of craftsmanship than other precast concrete products. Many combinations of shapes, sizes, colors, and textures are possible with this product. Typically, the fibers in a GFRC component make up at least 4% by weight of the total mix, with a minimum design thickness of 1/2 in. for the piece. The alkali-resistant glass fibers are specially designed for use in these components, and no others should be used (see Reference 24).

Recalling Art Deco architecture, the Esquire Plaza office tower and mixed-use building in Sacramento, Calif., takes its design cue from the two existing theater façades incorporated in the building. Precast concrete panels on the lower levels and GFRC on the upper portion made the highly articulated façade possible at an affordable cost. Architect: HOK/SF.; Photo: Ed Asmus Photography.

Located in downtown Chicago, Ill., the new residence hall for the School of the Art Institute is clad in GFRC panels, which emulate the look of the Windy City's historic buildings finished in terra cotta. The dormitory is composed of two connected buildings and a rear link. Architect: Booth Hansen Associates Inc., Chicago; Photo: ©Brian Fritz Photography.

GFRC is manufactured by hand-spraying a cement/sand slurry and glass fibers into molds of the desired shap and size. GFRC also can create highly detailed, ornamental pieces. Panels can be produced with or without a face mix of conventional concrete with decorative 1/4 in. maximum size aggregates. With a face mix, GFRC cladding panels, when given an architectural finish, are indistinguishable in exterior appearance from conventional concrete panels.

The variety of sculptural shapes made possible through the GFRC manufcturing process enables a wide range of creative architectural designs. The designer can choose from deep reveals to complex rectilinear and curvilinear shapes such as short radius curves, wide sweeping arcs, or 90-degree angles. The degree of such complex shaping has minimal effect on the cost of the panel due to GFRC's inherent design flexibility.

The low weight of GFRC panels decreases superimposed loads on the building's structural framing and foundation, providing potential savings in multistory construction and in areas with poor supporting soil. Its light weight also makes it ideal for use on low-rise frame buildings where heavier cladding systems would increase the size of framing members required.

Unless the panels have a functionally strengthening shape, GFRC properties dictate the use of stiffeners on panels of any appreciable size.

Stiffeners may be prefabricated, plant-attached steel studs or structural tubes, or integral ribs formed on the back of the panel by over-spraying hidden rib formers, such as expanded polystyrene strips or adding an upstanding single skin rib on the back of the panel. Either method stiffens the panel and provides a means for connection to the supporting structure. The steel panel frame is usually the more economical and preferred method for stiffening.

It is important when evaluating costs to realize that GFRC panels provide more than an exterior finish. The steel stud frame provides a surface for applying the interior finish, such as drywall, as well as the window frame. It also provides a cavity for installation of insulation, plus electrical, mechanical, and telephone conduits. This decreases the floor space needed for these items and eliminates trade overlap problems.

Panel design usually prevents stud or tube spacing from being coordinated with interior drywall modules. Therefore, it is recommended that if the studs are to receive interior drywall or similar treatment, drywall be mounted on shimmed, transverse furring channels rather than directly to the studs.

Windows should be attached directly to the head and sill tracks of the panel frame (or to a separate framing system) with only sealant contact to the GFRC.

Clay products, such as veneer-thickness brick, facing tile, and architectural terracotta, are not recommended due to volume change considerations. For more about this topic, see Reference 25.

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CHAPTER THREE b.

Integration & Coordination with Other Building Systems

Precast concrete is used in a wide range of building types, and its integration with mechanical, plumbing, lighting, and other systems can be achieved easily if designers understand the specifics of each project and precast concrete's requirements. Because of increased environmental demands, the proportion of costs related to mechanical and electrical installations in the overall budget has increased substantially in recent years. Working closely with the precaster to satisfy all of the service requirements will ensure an economical solution that produces cost-efficient, functional, and aesthetically pleasing results.

MECHANICAL

Spaces within stemmed precast concrete members, or the voids in hollow-core slabs, can be used for distribution ducts for heating, air-conditioning, and exhaust systems. In stemmed members, three sides of the duct are provided by the bottom of the flange and the sides of the stems. The bottom of the duct is completed by attaching a metal panel to the tee stems.

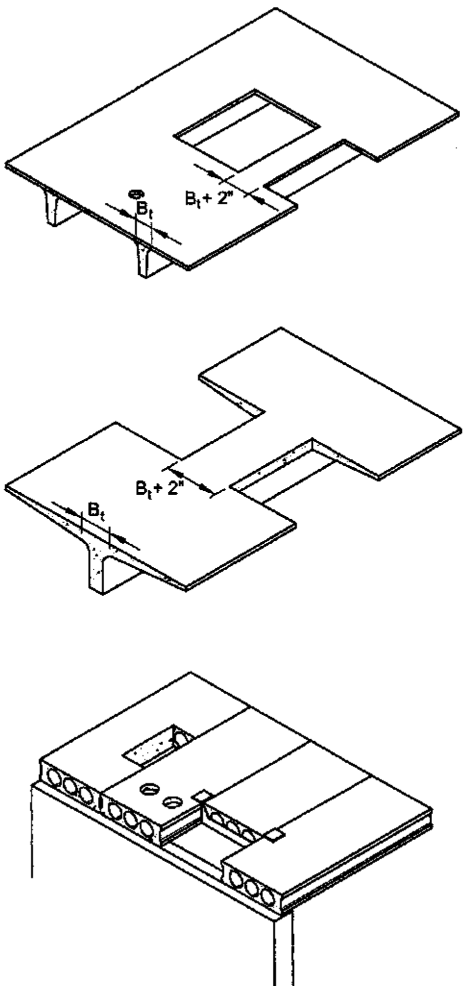
The ducts can be connected in several ways, including powder-activated fasteners, cast-in inserts, or reglets. Field-installed devices generally offer the best economy and ensure placement in the exact location required. Inserts should be cast-in only when they can be located during the design stage of the job, well in advance of casting the precast members.

If high-velocity air movement is desired, the enclosed space becomes a long plenum chamber with uniform pressure throughout its length. Diffusers are installed in the ceiling to distribute the air. Branches can consist of standard ducts installed along the column lines. Branch ducts of moderate size can also be accommodated by providing block-outs in the stems of tees or beams. These blockouts should be repeated in size and location to handle all conditions demanded by mechanical, electrical, or plumbing runs to remain economical, even if this results in some openings being slightly larger than required.

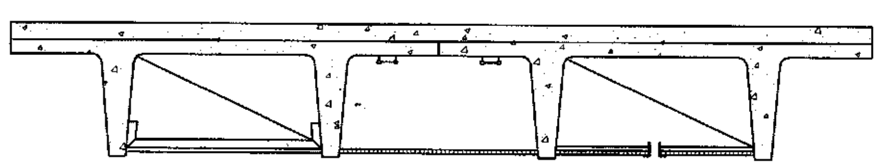
When ceilings are required, proper selection of precast concrete components can result in shallow ceiling spaces to accommodate required ducts, piping, and lighting fixtures.

Prestressed concrete box girders can serve a triple function as air conditioning distribution ducts, conduit for utility lines, and structural supporting members for the roof-deck units. Conditioned air can be distributed within the void area of the girders and then introduced into the building work areas through holes cast into the sides and bottom of the box girders. The system is balanced by plugging selected holes.

Vertical supply and return-air trunks can be carried in the exterior walls, with only small ducts needed to branch out into the ceiling space. In some cases, the exterior wall cavities are replaced with three- or four-sided precast concrete boxes stacked to provide vertical runs for the mechanical and electrical systems. These stacked boxes also can be used as columns or lateral-bracing elements (see Reference 1).



Large openings in floors and roofs are made during the manufacture of the units; small openings are field drilled. Some common types are shown here.



Metal panels attached at the bottoms of the stems create ducts, and diffuser panels provide a flush ceiling.

The three parking structures for the Shops at Willow Bend Mall in Plano, Tex., provide a light, bright interior. JPRA Architects Inc., Farmington Hills, Mich. Photo: J. Bendist Photographic/Dallas.

ELECTRICAL SYSTEMS

For many applications, designers can take advantage of prestressed concrete's reflective qualities and appearance by leaving the columns, beams, and ceiling structure exposed. The lighting system should parallel the stems of tee members to achieve uniform lighting free from distracting shadows.

A high level of illumination can be achieved at a minimum cost by using a reflective paint and proper spacing for high-output fluorescent lamps, which should be installed in a continuous strip. In special areas, lighting troffers can be enclosed with diffuser panels fastened to the bottom of the tee stems, providing a flush ceiling. By using reflective paints, the precast concrete lighting channels can be made as efficient as conventional fluorescent fixtures (see Reference 2).

The increasing use of networks for office machines, computers, and telephones and the continual adaptation of office space to new functions and staff needs have made adequate and flexible systems more critical in buildings to ensure this equipment can be handled efficiently. Since a cast-in-place topping is often placed on prestressed floor members, conduit runs and floor outlets can be easily buried within this topping. Burying conduits in toppings of parking structures, however, is not recommended because of the possibility for conduit corrosion.

Most systems can be included easily in a 2- to 4-in.-thick topping. When the system is placed in a structural-composite slab, the effect of ducts and conduits must be carefully examined and their locations coordinated with the placement of reinforcing steel. Voids in hollow-core slabs also can be used as electrical raceways. Spaces requiring large quantities of flexible wiring systems are typically addressed by specifying raised-access flooring.

Because of the high load-carrying capability of prestressed concrete members, high-voltage substations, with heavy transformers, can be located near the areas of consumption with little or no additional expense. For extra safety, distribution feeds can be run within the channels created by stemmed members. Such measures also aid the structure's economy by reducing the overall story height and minimizing maintenance expenses (see Reference 3).

BUILDING PENETRATIONS

Architectural precast concrete wall panels can be adapted to combine with preassembled window or door units. Door or window frames, properly braced to prevent bowing during concrete placement, can be cast into the panels, after which the glazing or doors can be installed, prior to or after delivery to the jobsite. If the glazing or doors are properly protected, they can also be cast into the panel at the plant.

Repetition of the design produces the most economy in a precast concrete panel, so windows and doors should be located in identical places for all panels whenever possible. However, virtually any design and window or door placement or combination of these units can be accommodated with precast concrete panels (see Reference 4).

Penetrations into precast concrete components are the most significant because they will allow energy transference that will reduce efficiency of HVAC equipment. A thorough analysis of air leakage is complex and involves parameters such as wall construction, building height, and orientation. An air barrier can stop outside air from entering the structure through the walls, windows, or roof, and it can prevent inside air from exfiltrating through the building envelope and any penetrations.

An air-barrier system must be virtually air-impermeable. Materials such as polyethylene, gypsum board, precast concrete panels, metal sheeting, or glass qualify as low air-permeable materials when joints are properly sealed. Materials that do not qualify include concrete block, acoustic insulation, open-cell polystyrene insulation, and fiberboard.

One relatively new approach to sealing joints involves using an interior foam backer rod and sealant along with a thermal-fusible membrane seal around the panel, which covers the gap between the structure and the panel. In the case of construction assemblies that do not lend themselves to sealing interior surfaces, the use of a separate vapor retarder must be considered (see Reference 5).

Fittings installed in outer walls, such as electrical boxes, should be completely sealed against moisture and air passage. They should be installed on the warm side of unbroken vapor retarders or air barriers that are completely sealed.

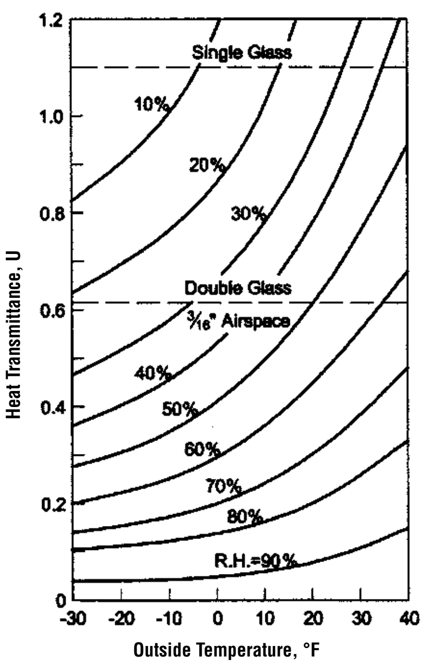
Velocity Multifamily Residential Condominiums, Hoboken, N.J.; Architect: Equus Design Group; Photos: Oldcastle Precast Building Systems.

VAPOR BARRIERS

Water-vapor diffusion occurs when water-vapor molecules diffuse through solid interior materials at a rate dependent on the permeability of the materials, the vapor pressure, and the temperature differentials. Generally, the cooler the outside temperature is, the greater the pressure is for the water vapor in the warm interior air to reach the cooler, drier, outside air.

Concrete in general provides a relatively good vapor retarder, provided it remains crack free. Permeance is a function of the ratio of the concrete's water and cementitious materials. A low ratio, such as those used in most precast concrete members, results in concrete with low permeance. Where climatic conditions require insulation, a vapor retarder is generally necessary to prevent condensation. A closed-cell insulation will serve as its own vapor retarder.

The function of a vapor retarder made of low-permeability material is to stop (actually, to retard) the passage of moisture as it diffuses through the assembly of wall materials. In temperate climates, vapor retarders should be applied on or near the warm side (inner surface) of assemblies. Vapor retarders can be structural or take the form of thin sheets or coatings. They can be positioned part way into the insulation, but they should be placed no farther inside than the point at which the dew-point temperature is reached to avoid condensation.



Relative humidity at which visible condensation occurs on inside surface. Inside temperature, 70 °F.

In climates with high humidities and high temperatures, especially where air-conditioning is virtually continuous, the ingress of moisture may be minimized by a vapor-retarder system in the building envelope near the outer surface. For air-conditioned buildings in hot and humid climates without extended cold periods, it may be more economical to use only adequate air-infiltration retarding systems rather than vapor retarders, since the interior temperature is rarely below the outside dew point.

High thermal-conductance paths reaching inward from or near the colder surfaces may cause condensation within the construction. High conductance paths may occur at junctions of floors and walls, walls and ceilings, and walls and roofs. They may also occur around wall or roof openings, at perimeters of slabs on the ground, and at connections.

When a material such as plaster or gypsum board has a permeance that is too high for the intended use, one or two coats of paint frequently will suffice to lower the permeance to an acceptable level, or a vapor barrier can be used directly behind such products. Polyethylene sheet, aluminum foil, and roofing materials are common applications. Proprietary vapor barriers, usually combinations of foil and polyethylene or asphalt, are typically used in freezer and cold-storage construction (see Reference 6).

MODULAR UNITS

Precast concrete provides an ideal material with which to create entire structures, particularly housing units, that require identical spaces that can be completed quickly. These designs work well because so many of the mechanical systems and other services can be installed in the units prior to delivery to the site, requiring only a final hookup after the unit is erected in its final location. This approach limits the amount of on-site labor that is required, saving time and adding safety. School classrooms, housing units, and prison cells all benefit from this type of fast, replicated unit and the advance installation of plumbing, electrical, mechanical, and even finishing systems.

For housing or school applications, electrical conduit and boxes can be cast into the precast wall panels, which requires coordination with the electrical contractor. The metal or plastic conduit is usually pre-bent to the desired shape and delivered to the casting bed already connected to the electrical boxes. Telephone and communication accessories have also been cast-in using the same procedure.

Plumbing units are often connected and assembled prior to delivery for kitchen or bathroom modules. To eliminate a double floor, the module can be plant-built on the structural member or the walls of the unit can be designed for all fixtures to be wall-hung. Some core modules also feature HVAC components, which are packaged in one unit. These modules can be accommodated in prestressed structural systems by placing them directly on the prestressed members with shimming and grouting (see Reference 7).

Prisons maximize the use of these modules by creating multiple-cell units. They generally consist of cell walls, chase walls, and a floor and/or ceiling. All components of each cell are installed at the plant. These components include windows, beds, mirrors, desks, air vents, light fixtures, sinks, water closets, and associated chase plumbing and wiring. Erection at the site is rapidly completed and field work is greatly reduced. The result is a safe, functional, and economical prison facility in the shortest construction time (see Reference 8).

Photos: Tindall Corporation/Correctional Division.

References:

1. Chapter 9.10.4, "Ductwork," PCI MNL-120-04: *PCI Design Handbook, Sixth Edition.*
2. Chapter 9.10.2, "Lighting and Power Distribution," PCI MNL-120-04: *PCI Design Handbook, Sixth Edition.*
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CHAPTER THREE C.

Team Responsibilities

Design and construction of a high-quality structure is a complex process requiring teamwork among all of the professionals involved. The project's success relies on defining the scope of work and the responsibilities of the involved parties by means of contract documents. To that end, the scope of the precast concrete work and the responsibilities of each party should be established early in the project's development to maintain the schedule.

©PhotoDisc.

One of the basic principles of the construction industry is that responsibility and authority must go hand in hand. Another principle is that every party should be responsible for its own work. These principles are sometimes violated in practice, leading to adversarial situations that can damage a project's success.

The complexity of structures today makes it essential to have design input from subcontractors, whether the project will follow a conventional design-bid build, design-build, or alternative construction formats. This input can take three forms:

- Value-engineering proposals
- Response to performance requirements
- Suggestions for design alternatives

Gaining the precaster's aid and insight during the conceptual stage can ensure that the design provides the most cost-efficient, aesthetically pleasing, and functional plan possible. The precast concrete manufacturer can consider many aspects, including transportation and erection, that may otherwise be overlooked and become costly after the fact (see Reference 1).

(For more on the benefits provided by early input by the precaster, see Chapter 1D, "Construction Issues.")

THE DESIGN PROCESS

The design considerations for the precast concrete components of a project consist of three stages:

1. **Conceptual design.** The general ideas of what the owner wants to accomplish in function, image, budget, and other factors can be discussed with the precaster. This will often aid the project's completion even if the original intent was not to use precast concrete, especially if stone or masonry was desired.

2. **Preliminary design.** This planning stage gains from precaster input on the general layout, overall dimensions, typical details, and other specifics. This input can be relatively simple, such as with the layout of a hollow-core flooring plan, or complex if the design will feature a total-precast concrete structural system and intricate finishes on architectural precast concrete components.

3. **Final design.** The specific details of the components, such as strand patterns, connections, embedded items, and other elements, are decided at this point, and shop drawings are produced.

Because of the range of input that can be provided at each stage, the precaster typically participates in the design process with the project-management team, especially to provide input on costing. The capacity to participate varies with each precaster and with each job.

In general, the precaster can provide the following information:

- Design properties unique to his or her product, such as section properties, normal concrete strengths, and strand patterns (if needed by the structural engineer).
- Detailed specifications for the manufacture of the components using proprietary equipment.
- The detailed design of the specific components as agreed in the preliminary design phase.
- Detailed layout drawings locating each component type in the structure.
- Support and joint details.
- Product drawings showing details, including dimensions and the location of lifting and connection hardware.
- The erection procedure.

In some cases with fast-track projects, some precast concrete components go to the shop-drawing stage before the final specifics of the design are completed. Because precast concrete components combine customization with a highly controlled manufacturing process, fabrication in some cases can go forward on this accelerated basis to meet a tight deadline that cannot wait for all of the contract drawings to be completed first. This ability can keep a project on schedule when the use of other materials would not have been able to improve the timeframe (see Reference 2).

RESPONSIBILITIES OF THE ARCHITECT

The architect has responsibility and authority for all aspects of the precast concrete design. This generally requires that a registered professional engineer or architect accepts responsibility as the engineer of record for ensuring that these requirements are met. The engineer of record seals the contract documents, which constitute the structural design. They are customarily submitted to regulatory authorities for a building permit.

The engineer of record will also approve shop drawings and may have other ongoing responsibilities during construction.

The architect may specify in the contract documents that design services for portions of the work are to be provided by the precaster and must be performed by a licensed engineer employed or hired by the precaster. The division of responsibility between the engineer of record and the precaster's structural specialty engineer must be worked out in advance.

The contract and the design documents should state clearly the scope of both the precast concrete design and review responsibilities, as well as the responsibilities of others providing design services.

The contract drawings prepared by the architect should provide the overall geometry of the structure, member, or panel sizes (including permissible alternative sizes) and typical connection locations and concepts. This detail allows everyone to estimate based on the same information. These drawings and the specifications become a part of the contract documents used by contractors to construct the structure (see Reference 3).

The contract documents provided by the architect should include:

- **Reveals or design articulation**, letting the precaster determine panel sizes suitable to their handling and erection capabilities.
- **General performance criteria**, including concrete strength requirements for loading, deflection requirements, temperature considerations, and any tolerance or clearance requirements for proper interfacing with other parts of the structure.
- **The order of priority** in which the project contract, specifications, or drawings prevail in the event of conflict.
- **All aesthetic, functional, and structural requirements** that impact the precast concrete fabrication.

To delineate responsibility for all interfaces of precast concrete components with other materials, the architect also should define:

- **Precast concrete components** to be designed by the precaster, stating who takes responsibility for conditions at interfaces with other parts of the structure.
- **Details or concepts of supports, connections, and clearances** that are part of the structure designed by the architect and that will interface with the precast concrete components.
- **Permissible load transfer points** with generic connection types indicated so the precaster does not make assumptions during bidding.

The architect and engineer of record should review submitted designs, calculations, and shop drawings to ensure they conform to design criteria, loading requirements, and design concepts as specified in the contract documents. This review does not relieve the precaster and the precast concrete engineer of their design responsibilities (see Reference 4).

The format and extent of information supplied by the architect will impact the precaster's responsibility. The accompanying chart indicates three ways in which contract information can be supplied by the architect and the activities for which the precaster is thereby responsible.

DESIGN RESPONSIBILITIES

Contract Information Supplied by Design Team	Responsibility of the Precaster
OPTION I	
Provide complete drawings and specifications detailing all aesthetic, functional, and structural requirements including design criteria, plus dimensions.	The precaster should make shop drawings (erection and production drawings), as required, with details as shown by the designer. Modifications may be suggested that, in precaster's estimation, would improve the economics, structural soundness, or performance of the precast concrete installation. The precaster should obtain specific approval for such modifications. Full responsibility for the precast concrete design, including such modifications, remains with the designer. Alternative proposals from a precaster should match the required quality and remain within the parameters established for the project. It is particularly advisable to give favorable consideration to such proposals if the modifications are suggested so as to conform to the precaster's normal and proven procedures.
OPTION II	
Detail all aesthetic and functional requirements but specify only the required structural performance of the precast concrete units. Specified performance should include all limiting combinations of loads together with their points of application. This information should be supplied in such a way that all details of the unit can be designed without reference to the behavior of other parts of the structure. The division of responsibility for the design should be clearly stated in the contract documents.	The precaster has two alternatives: (a) Submit erection and shape drawings with all necessary details and design information for the approval and ultimate responsibility of the designer. (b) Submit erection and shape drawings and design information for approval and assume responsibility for the structural design; that is, the individual units, but not their effect on the building. Precasters accepting this practice may either stamp (seal) drawings themselves or commission engineering firms to perform the design and stamp the drawings. The choice between the alternatives (a) and (b) should be decided between the designer and the precaster prior to bidding with either approach clearly stated in the specifications for proper allocation of design responsibility. Experience has shown that divided design responsibility can create contractual problems. It is essential that the allocation of design responsibility is understood and clearly expressed in the contract documents.
OPTION III	
Cover general aesthetic and performance requirements only and provide sufficient detail to define the scope of the precast concrete work.	The precaster should participate in the preliminary design stage and the development of the final details and specifications for the precast concrete units and should work with the design team to provide an efficient design. The precaster provides the engineering design of the precast concrete units and their connections to the structure and should work with the design team to coordinate the interfacing work. The precaster should submit shop design information for approval and drawings at various stages of completion for coordination with other work.

Source: Table 4.1.1: Design Responsibilities; Chapter 4, Section 4.1.2, "Responsibilities of the Architect," PCI MNL-122-07: Architectural Precast Concrete, Third Edition.

KEY ARCHITECTURAL DESIGN ISSUES

The architect should make sure that the contract documents address the issues that affect a precaster's bid. The drawings should provide a clear interpretation of the configurations and dimensions of individual units and their relationship to the structure and to other materials. Contract documents that lack detail may extend shop-drawing time and could lead to confusion over the scope of work and impact schedule.

The contract documents should supply the following data:

- Elevations, sections, and dimensions necessary to define the sizes and shapes (profiles) of each type of precast concrete component.
- Locations of joints real (functional) and false (aesthetic).
- Required materials, color, and finish treatment for all surfaces with a clear indication of which surfaces are to be exposed to view when in place.
- Corner details.
- Details for jointing and interfacing with other materials (coordinated with the general contractor) including windows, roofing, and other wall systems.
- Openings for services and equipment with their approximate size and location.
- Details for special or unusual conditions, including fire-endurance requirements.
- Governing building codes, design loads, and deflection limitations.
- Specified dimensional tolerances for the precast concrete and the supporting structure, location tolerances for the contractor's hardware, clearance requirements and erection tolerances for the precast concrete.
- Support locations for gravity and lateral loads.
- Building location and site access.
- Delineation of any unusual erection sequence requirements.

Logan International Airport Central Parking Garage Expansion, Boston; Architect; TAMS/Fennick/McCredie Architecture Ltd.; Photo: Blakeslee Prestress Inc. (top right), ©PhotoDisc (bottom right).

The precaster will use this information from the contract drawings and documents to generate shop (erection) drawings and design calculations. The shop drawings should detail elevations showing panel sizes, surface features and panel relationships. Detail sheets should show panel cross-sections, special edge conditions and feature details, and they should specify connections showing mechanisms and locations of load transfers to the supporting structure.

Greater economy and flexibility will be achieved by allowing the precaster to suggest configurations and select which joints are false and which are real in the panelization. The architect should then review all shop drawings to ensure they conform to the contract documents.

Small mockups are encouraged, as they help verify the appearance of the completed façade and help clarify actual field-construction techniques and material interface issues. When the units have returns, the same size return should appear in the mockup panels. It is the architect's responsibility to determine the standards of acceptability for surface finish, color range, and remedial procedures for defects and damage.

After the project is erected and detailed, the architect should immediately prepare a punch list setting forth, in accurate detail, any items that are not in accordance with the contract documents so the proper corrective action can be taken. All repairs should conform to the architect's requirements for matching the original finish and should be structurally sound.

When advised by the precaster that the listed items have been completed, the general contractor, construction manager, architect, and engineer should check the corrections as needed. After the precast concrete components have been accepted, subsequent responsibility and liability for their condition rests with the general contractor (GC)/construction manager (CM). (For more on these responsibilities, see Reference 5.)

THE BID PROCESS

When selection of the precaster cannot be negotiated or controlled by the owner or architect but is governed by an open-bid situation, these steps should be followed:

1. **Verification of architects concepts and systems.** A review of the proposed precast concrete assumptions during the early design development stage of the architectural contract documents should be arranged with at least one local precaster. Items to be reviewed include:
   - Panelization, form families, piece sizes, weights, and reveals.
   - Potential shipping and erection issues.
   - Architectural concepts for structural supports or connections for the precast concrete so that the architect can communicate to the engineer of record about any support requirements.

- Desired aesthetic issues relative to mixture(s) and finish(es) and the sample process.
- The architect's intent for any interfaces with adjacent systems, such as windows, roofing, or building entrances.
- Mockups or other special testing requirements.

2. The prebid conference. A meeting with all precasters planning to bid on the project should be held at least three weeks prior to the bid date. Items to be discussed include:

- Specifications and any special provisions.
- Design responsibilities and lines of communication.
- The architect's approved finish samples with information on the mixture design, where applicable.
- Prebid submittal requirements, such as proposal drawings and finish samples.
- Project schedule, shop-drawing submittal requirements, and architectural-review turnaround times.
- Panelization.
- Mockups, if applicable.
- Potential problems, discrepancies, or both found in the contract documents.
- How and where the project's precast concrete will be structurally attached to the building frame.
- Interfacing with other trades.
- Responsibility for designing, providing and installing embedded items, connection hardware attached to the structural steel, bracing, and other structural items.
- Hardware and reinforcement finishes.
- Special erection needs, such as access, crane limitations, and sequences, as well as logistics.
- Responsibility for caulking.

3. **The post-bid scope review.** A final meeting allows the architect and general contractor to review the precaster's proposal and confirm the company's ability to satisfactorily produce the project and conform to the design concepts and finish requirements. This review should include:
   - Proposal drawings that express the architectural precast concrete panelization and structural attachment concepts.
   - Finish samples.
   - The history of the precaster's company and confirmation of the plant's PCI certification.
   - A list of comparable projects, references, and financial capability.
   - Key schedule items such as mockup panels, shop drawings and design submittals, mold production, production start and duration, and erection start and duration.
   - Qualifications to the bid that can be listed and reviewed.

If the project allows a negotiated precast concrete contract, and the precaster is brought on board during the initial stages of development, prebid and bid submittal information can be minimized.

4. **Construction coordination.** This meeting should be held at the jobsite after the precast concrete and erection contracts have been awarded. The general contractor should conduct frequent jobsite meetings to coordinate precast concrete design and erection with the work of other trades and general building construction. These meetings should include the subcontractors whose work is impacted by the precast concrete design and erection.

The coordinating meetings should consider a variety of details, including:

- Loading, delivery sequence, and schedules.
- Types of transportation.
- Routes of ingress and egress for delivery trucks and erection cranes.
- Handling techniques and devices.
- Connections.
- Erection methods and sequences.
- The effects of temporary bracing on other trades.
- Offsite storage and protection.

Additional questions about site access, street use, sidewalk permits, oversized loads, lighting, or unusual working hours should be addressed at this time. (For more on the prebid process, see Reference 6.)

THE PRECASTER'S RESPONSIBILITIES

The precaster will perform component design of the members when this task is required by the contract. The precaster normally accepts responsibility for design of the connections when the forces acting on the connections are defined by the engineer. Precast concrete reinforcement is determined by code and industry-standard design, unless otherwise defined by the contract documents.

The precaster's responsibilities include:

- Value engineering to improve construction economics, structural efficiency, and precast concrete performance.
- Panelization (panel sizing and joints), which is typically designed first.
- Connection details.
- Detailed shop drawings and design calculations, showing all design criteria, identifying all materials and illustrating panel interfaces with each other, the structure, and adjacent materials.
- Designing panel and connection hardware for the specified loads.
- Selecting, designing, and locating hardware for the specified loads and panel reinforcement.
- Items associated with the precaster's methods of handling, storing, shipping, and erecting the precast concrete components.
- If necessary, creation of an erection and bracing sequence, developed in conjunction with the erector, engineer, and general contractor, to maintain the stability of the structure during erection.

The extent of additional design responsibility vested with the precaster should be clearly defined in the project documents prepared by the architect.

Quality control for product manufacturing is supplied by the precaster according to provisions contained in a comprehensive quality system manual developed by the precaster, in addition to requirements contained in PCI MNL-117, *Manual for Quality Control for Plants and Production of Architectural Precast Concrete Products*. Quality assurance is provided through the precaster's participation in the PCI Plant Certification Program. Additional inspection at the owner's expense may be required by specification through the owner's quality-assurance agency (see Reference 7).

VALUE ENGINEERING AND DESIGN-BUILD APPLICATIONS

Owners may allow, or even encourage, considerations of alternative construction schemes on a project. In such cases, the design drawings frequently are not as definitive as in fully developed designs. When such alternatives use precast concrete as the primary structural system, the precast engineer or another qualified consulting engineer may be designated as the engineer of record.

If a fully developed design is included in the contract documents, a contractor proposing an alternative for some part of the structure should consider the effect of the alternative on all other parts of the structure and provide all necessary design changes.

Owners also may directly seek proposals from general contractors who are willing to prepare design-build proposals. The general contractor may employ a professional engineer or subcontract the design to a firm that serves as the engineer of record. Typically, the precaster serves as a subcontractor of the general contractor, and he or she accepts responsibility for component design of the produced member.

Local regulatory authorities may approve design documents for starting construction without final design of the precast concrete members. In some cases, the design can be performed and submitted at a later time, often in conjunction with preparation of shop drawings. The engineer of record may require that a registered engineer seal the documents that depict the precast design.

PCI is keenly aware of the competitiveness in the marketplace for building systems. Along with high quality, it is essential that a structure have structural integrity and performs as intended. Because the construction process involves many parties, it is essential that work assignments and responsibilities be clearly defined in the contractual arrangements, whatever form they take (see Reference 8).

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1. Chapter 4, Section 4.1, "Design & Construction Responsibility," PCI MNL-122-07: *Architectural Precast Concrete, Third Edition.*
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CHAPTER THREE

d.

Initial & Life-Cycle Costs

Joe Serna Jr. California EPA Headquarters; Sacramento, Calif.; Architect: A.C. Martin Partners; Photo: Walters and Wolf Precast.

A variety of cost calculations is required on every project to determine what design approaches will reap the most advantages for the owner and allow budgets to be allocated most efficiently. Initial, in-ground costs are the most obvious expenses, but hidden and longer-term costs are becoming more significant as owners and designers study the budget impact of various specifications.

The primary philosophy that has come to the fore looks at the project holistically, understanding that every system and decision impacts others. The goal is to ensure that all products and systems work together to enhance each other without creating redundancy or inefficiencies.

Added insulation and other energy efficiencies, for instance, may allow the installation of smaller HVAC equipment than would be needed otherwise. Siting the building certain ways and using more glass may allow fewer light fixtures to be installed. Using products that can enclose the building quickly avoids winter slow downs and gets crews inside quicker, bringing the project online faster so revenues can be generated quicker.

Maintenance needs throughout the building's life must also be considered. These expenses come from the operating budget rather than the construction budget, and so they often were overlooked in the past when designing the building. Today, owners and designers are acknowledging that all budgets must be considered, and labor and material costs that keep a building operating efficiently through its life are part of the equation at the design phase.

Durability, such that a building does not need to have its exterior refurbished or possibly replaced in 20 years, has also become more of a consideration. The entire life-cycle costs of a project are being calculated, and each material choice must justify its value today, tomorrow, and many years from now.

IN-GROUND COSTS

Initial or in-ground costs are the most obvious and most significant when determining budgets and where to allocate funds for the construction of a building. Precast concrete components provide a variety of savings to a project in ways that are not always considered when looking at upfront costing versus other materials, including masonry and curtain wall. These savings include:

SPEED. Precast concrete components provide a variety of ways to speed the construction process, from design through fabrication and erection. These efficiencies can shave as much as one-third of the time needed for construction, meeting tight deadlines and generating revenues quicker. Time can be saved through:

- **The design process.** It takes less time to design a precast concrete building than one built of other materials, due to the lessened detail required in precast concrete's panelized system and the ability to quickly replicate components on each floor or wing.
- **The fabrication process.** Precast concrete components can be fabricated while permitting and foundation work progress, so they are ready to begin erection as soon as foundations are complete. As a single-source supplier for a large portion of the structural system, precasters help maintain the critical-path scheduling.
- **The erection process**. Foundations can be placed one day and precast concrete loadbearing or non-loadbearing panels can be erected as soon as the foundations have cured sufficiently. Wall panels, double tees, and hollow-core planking also erect quickly, often cutting weeks or months from the schedule. This speed allows construction to get into the dry quicker. The fast enclosure also lessens concern for weather or material damage during erection, reducing the contractor's risks and costs.
- **The finishing process.** Precast concrete insulated sandwich panels create a finished interior wall that avoids the time and cost of furring and drywalling. Architectural panels can have a variety of colors and textures cast into them, including several in one panel, eliminating the need to field-set trim pieces or paint the façade after the structure is built. (For more on this aspect, see Reference 1.)

NBSC Headquarters Building, Greenville, S.C.; Architect: Neal + Prince & Partners; Photos: Metromont Corporation.

Day 1 — Foundation ready.

Day 7 — Building begins taking shape.

DESIGN ECONOMY. The custom, sculptured designs that are possible with precast concrete may be achieved within a limited budget by selecting economical aggregates and textures combined with repetitive units and effective production and erection details. The key factors in designing economically with architectural precast are:

- **Repetition.** By reusing the same dimensions for components, the same molds can be used, minimizing the total number needed and the changes between casting. Efficiency is created by making it possible for similar, if not identical, shapes to be produced from the same basic (master) mold and by minimizing the time required to disassemble a mold and reassemble it for the next piece. Mold costs range from hundreds to thousands of dollars per mold, depending on size, complexity, and materials used.

Effect of Repetition on Panel, Square-Foot Cost

Number of Reuses	Panel Size (square feet)	Mold Cost	Cost per Square Foot
1	200	$5,000	$25.00
10	200	$5,000	$2.50
20	200	$5,000	$1.25
30	200	$5,000	$0.83

Source: PCI MNL-122-07: Architectural Precast Concrete, Third Edition. Art. 2.2.2 Mold Costs.

Note: This table reflects a typical cladding application of precast concrete architectural panels. The same or a similar process can be used for a total-precast concrete structure.

Day 15 — Interior shear walls.

Day 25 — Shear structure.

Day 44 — Structurally and architecturally dry.

- **Average piece size.** Precast concrete pricing is primarily determined by the size of the pieces and piece repetition. Pricing depends more on the number of pieces than the size of the project. A 100-piece project of large panels can be less expensive per square foot than a 1000-piece project of much smaller panels on the same size building. Labor functions drive pricing more than material cost, and each new piece, particularly different shapes or sizes, drives up the amount of labor needed to create and erect a component. It is most economical to cover a larger portion of the building's exterior with fewer precast concrete panels.

During a project's preliminary design, a precast concrete project can be budget "guesstimated" on a square-foot basis. Although this provides a good starting point, it is not recommended that designers rely on this method alone. A square-foot take-off can differ depending on the precaster, general contractor, and architects involved and on the procedures used. Work-scope criteria typically isn't known, and it impacts the final budget. Erection access and crane requirements also are not defined, and back-forming and other details cannot be predicted (see Reference 2).

Effect of Panel Size on Erection Cost, per Square Foot
(based on a minimum erection time of one month)

Panel Size (Square Feet)	Erection Cost per Piece, $/Square Foot			
	$500	$1,000	$1,500	$2,000
50	10.00	20.00	30.00	40.00
100	5.00	10.00	15.00	20.00
150	3.33	6.67	10.00	13.33
200	2.50	5.00	7.50	10.00
250	2.00	4.00	6.00	8.00
300	1.67	3.33	5.00	6.67

Source: PCI MNL-122-07: Architectural Precast Concrete, Third Edition. Art. 2.2.4 Panel Size/Panelization.

Note: This table reflects a typical cladding application of precast concrete architectural panels. The same or a similar process can be used for a total-precast structure.

Material Efficiency. Precast concrete saves money by replicating the look of more expensive materials, such as natural stone (granite, marble, limestone, sandstone, or slate). Veneers of these materials also can be cast into the face of the precast concrete components, saving the expense of full-thickness pieces. Brick-faced precast concrete also eliminates labor costs and speeds up construction.

Precast concrete components can save money by using single components to serve several functions. Hollow-core planking and double tees, for instance, can be used as a combined ceiling/flooring unit, saving material costs and speeding construction further due to less labor. This is enhanced with total-precast concrete systems, which can combine architectural and structural functions into one piece (see Reference 3).

In parking structures, precast concrete spandrel panels are used as a vehicle-impact restraint in addition to providing a perimeter design feature. This eliminates the need for an upturned cast-in-place concrete beam or cable system (see Reference 4).

Construction Efficiency. Because precast components are fabricated under factory-controlled conditions at a plant, harsh winter weather does not impact the production schedule or product quality. This approach means they can be erected through the winter months to meet a tight schedule, cutting overhead costs, and opening the building for occupancy faster.

Producing the components in a plant also ensures tight tolerances, which will facilitate erection and require fewer field adjustments that other methods may need to complete the structure.

Precast concrete panels inset with thin bricks or cast using formliners to resemble stone require only one trade, eliminating costly and time-consuming masonry as well as other trades from the site. (For more on this aspect, see Reference 5.)

Hidden Costs. Precast concrete's speed of construction can reduce the construction time frame by several months. This results in less time to carry financial bonds, lower contractor overhead costs and risk, elimination of expenses for nonprecast-related equipment, and reduced subcontractor costs by giving more responsibility to a single-source supplier (see Reference 6).

References:

1. MK-34-03: *Precast Concrete Makes the Grade For K-12 School Facilities*, p. 4: "Meeting Deadlines."
2. Chapter 2, Section 2.2, "Design Economy," MNL-122-07: *PCI Architectural Precast Concrete Manual, Third Edition.*
3. MK-34-03: *Precast Concrete Makes the Grade For K-12 School Facilities*, p. 2, "Total Precast Concrete Systems Meet Schools' Total Lifetime Needs."
4. DN-11-02: Designer's Notebook: *Design Economy.*
5. MK-34-03: *Precast Concrete Makes the Grade For K-12 School Facilities*, p .3: "Cost Effectiveness."
6. MK-34-03: *Precast Concrete Makes The Grade For K-12 School Facilities*, p.3: "Cost Effectiveness."

Resources:

CD/IGS-8-02: Commercial Building CD-ROM.

DN-11-02: Designer's Notebook: *Design Economy.*

DN-12-02: Designer's Notebook: *Benefits & Advantages.*

MK-21-98: *Parking Structures: Team Solutions Timeline.*

MK-22-98: *The Precast Prestressed Advantages for Owners and Developers.*

MK-35-03: *Precast Concrete Panels: Tilt-up Doesn't Measure Up.*

MAINTENANCE COSTS

Generally, precast concrete components, even architectural precast concrete panels exposed to weather, require little maintenance. A regular inspection and routine recaulking of cladding panels every 15 to 20 years are all that may typically be required. Panels can be washed with strong chemicals and cleaners without losing their color, and UV rays will not cause them to fade, as will happen with paint.

Parking structures, more than any other building type, require routine maintenance. Unlike other buildings, the structural components are exposed directly to weather and other environmental conditions. Extreme temperature changes, rain, snow, deicing salts, road grime, and dampness directly influence the durability of parking structures and have the potential to create performance problems. The severity of these problems will depend on the structure's location, environmental conditions, and maintenance schedule.

Based on national surveys, precast concrete parking structures offer superior resistance to deterioration. Components produced by PCI-certified plants in particular offer a controlled environment where durable concrete with specialty curing can be created that cannot be achieved in the field. However, without proper maintenance, any structure's life will be compromised.

Besides increasing service life and reducing long-term structural repairs, a comprehensive maintenance program for a parking structure will produce a cleaner, safer, and more user-friendly atmosphere that encourages repeat business and discourages littering and loitering. It is essential that a maintenance program be a major part of the operation of all parking structures. A routine maintenance program should be set up immediately upon turnover of the parking structure, and the precaster can help in preparing a schedule of activities (see Reference 1).

Hull Street Parking Structure, Athens, Ga.; Architect: Smallwood, Reynolds, Stewart, Stewart & Associates Inc.; Photo: Jim Roof.

In general, there are three types of maintenance:

1. **Housekeeping.** This includes general cleaning, floor washing, cleaning of debris from expansion joints, touchup of painted surfaces, upkeep of landscaping, repainting stripes and graphics, cleaning lighting fixtures, removing graffiti, etc. (see Reference 2).

2. **Prevention Maintenance.** This focuses on periodic checkup, cleaning, and restoration of all components, including structural, architectural, and mechanical elements, as well as equipment maintenance and safety systems. Such activities will prevent premature deterioration of the structure and unexpected failure of mechanical components (see Reference 3).

3. **Structural Repairs.** Even the best maintained parking structure may occasionally require some structural repairs. Repairs may be needed to fix scaling, spalling, cracking, or delamination. In addition, flange connections should be checked for weld failures or corrosion damage. An experienced engineer should examine these conditions to determine the best course of action (see Reference 4).

Having an engineer experienced in this type of construction perform a periodic structural audit will ensure that any conditions are caught before they become a major expense. Performing such an audit every three to four years with experienced personnel using the proper testing equipment is recommended. The first audit should take place immediately after construction is completed so a basis for future audits is established (see Reference 5).

References:

1. Chapter 1.0, "Introduction," MNL-136-04: *Maintenance Manual for Precast Parking Structures.*
2. Chapter 2.1, "Housekeeping," MNL-136-04: *Maintenance Manual for Precast Parking Structures.*
3. Chapter 2.3, "Prevention Maintenance," MNL-136-04: *Maintenance Manual for Precast Parking Structures.*
4. Chapter 2.4, "Structural Repairs," MNL-136-04: *Maintenance Manual for Precast Parking Structures.*
5. Chapter 2.5, "Periodic Structural Audit," MNL-136-04: *Maintenance Manual for Precast Parking Structures.*

Resources:

CD/IGS-8-02: Commercial Building CD-ROM.

DN-11-02: *Designer's Notebook: Design Economy.*

DN-12-02: *Designer's Notebook: Benefits & Advantages.*

MK-21-98: *Parking Structures: Team Solutions Timeline.*

MK-22-98: *The Precast Prestressed Advantages for Owners and Developers.*

MK-35-03: *Precast Concrete Panels: Tilt-up Doesn't Measure Up.*

Union Plaza Transit Terminal and Parking Garage, El Paso, Tex. The use of an all-precast concrete strucure, including double tees, beams, columns, and shear walls speeded construction and maximized interior layout space.

LIFE-CYCLE COSTS

Determining life-cycle costs, or all of the expenditures incurred over the lifetime of a particular structure, has gained a higher profile as owners and architects realize the impact of long-term expense on the operating cost of a building and its effect on the structure's overall return on investment. The focus on sustainable design in particular has made owners and designers examine the long-term benefits and costs of various decisions.

Performing a life-cycle analysis, however, requires a variety of assumptions and complexities. Many types of life-cycle analyses can be created, and the best one to meet the owner's needs will vary based on the project, the owner, and the goals.

Economic versus Environmental

A life-cycle analysis can be done in terms of the economic or environmental life-cycle cost impact. Although the two approaches are different, they each consider the impacts of the building design over the life of the building, an essential part of sustainable design.

When the energy and resource impacts of sustainable design are considered over the life of the building, a sustainable design often becomes cost-effective. Conversely, when the energy-consuming impacts of a low, first-cost design are considered over the life of the building, the building may not be as attractive of an investment (see Reference 1).

A life-cycle cost analysis is a powerful tool used to make economically sound decisions for selection of materials. Costs at any given time are discounted back to a fixed date, based on assumed rates of inflation and the time-value of money. A life-cycle cost is given in terms of dollars and represents the construction cost plus the present value of future utility, maintenance, and replacement costs over the life of the building.

Using the widely accepted life-cycle cost analysis, it is possible to compare, in a fair way, the economics of alternatives that may have different cash-flow factors but provide a similar standard of service. The result is financial information for decision making, which can be used to balance capital costs and future repair or maintenance costs.

Quite often, those designs with the least first cost for new construction will require higher costs during the building life. Because they avoid a high first cost, they require more maintenance over time and thus have a higher life-cycle cost. As a very durable material, precast concrete may have somewhat higher initial costs but lower life-cycle costs because they require little maintenance after they are fabricated and erected.

The Building Life-Cycle Cost software from the National Institute of Standards and Technology (NIST) provides economic analysis of capital investments, energy and operating costs of buildings, systems, and components. The software includes the means to evaluate costs and benefits of energy conservation. It complies with ASTM standards related to building economics and Federal Energy Management Program requirements.

Accepted methods of performing life-cycle cost analyses of buildings assume a 20-year life, with the building maintaining 80% of its residual value at the end of this period. However, buildings actually last hundreds of years if they are not torn down due to functional obsolescence.

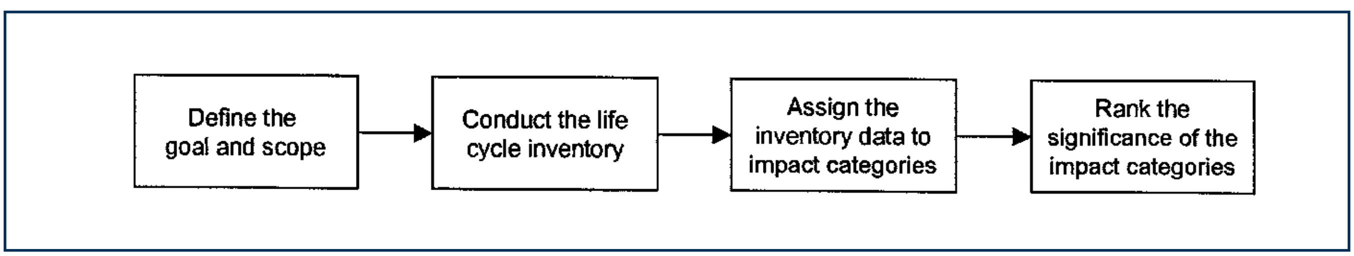
Sustainability practitioners advocate that the building's foundation and shell should be designed to last for 200 to 300 years. The building's long-term flexibility can be increased by allowing extra capacity in the columns for extra floors and floor loads as well as extra capacity in roofs for roof-top gardens.

Speculative-building developers often design for a return on investment in seven years and generally do not buy into the life-cycle cost approach. Similarly, minimum code requirements for energy-conserving measures in the building shell are generally calculated for five years, meaning initial insulation levels should pay for themselves in that time. Since it is difficult and costly to add more insulation to the building shell after it has been constructed, the 5-year payback for insulation is not consistent with a 100-year building use.

Advanced building-design guidelines from the New Buildings Institute (www.NewBuildings.org) and others specify insulation levels for those who want to build cost-effective buildings above minimum code level. Alternatively, thermal mass and insulation can be included in the life-cycle cost analysis to determine cost-effective levels. However, this requires whole-building energy analyses, to determine annual costs to heat and cool the building. Economic levels of insulation depend on the climate, location, and building type. (See Reference 2.)

Creating a Life-Cycle Assessment

A life-cycle assessment (LCA) is an environmental assessment of the life cycle of a product. An LCA looks at all aspects of a product life cycle, from the first stages of harvesting and extracting raw materials from nature to transforming and processing these raw materials into a product, using the product and ultimately recycling or disposing of it back to nature. An LCA consists of four phases:



A life-cycle assessment of a building is necessary to evaluate the environmental impact of a building over its life. It includes impacts due to:

- Extraction of materials and fuel used for energy.
- Manufacture of building components.
- Transportation of materials and components.
- Assembly and construction.
- Operation, including energy consumption, maintenance, repair, and renovations.
- Demolition, disposal, recycling, and reuse of the building at the end of its functional or useful life.

A full set of impacts includes land use, resource use, climate change, health effects, acidification, and toxicity.

A life-cycle assessment involves a time-consuming manipulation of large quantities of data. A model such as Simapro provides data for common building materials and options for selecting LCA impacts. The Portland Cement Association (www.cement.org) publishes reports with life-cycle inventory data on cement and concrete. All models require a separate analysis of annual heating, cooling, and other occupant loads using a program such as DOE2.1e.

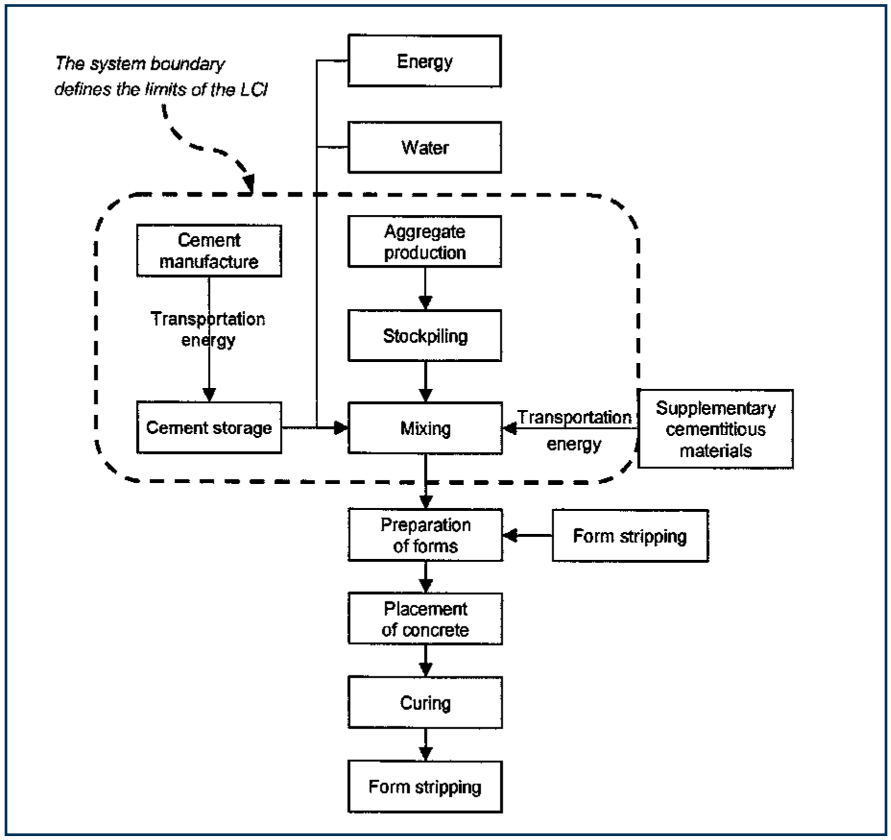
Creating an LCI

A life-cycle inventory (LCI) is the first stage of a life-cycle assessment. An LCI is an accounting of all the individual environmental flows to and from a product throughout its life cycle. It consists of the materials and energy needed to make and use a product and the emissions to air, land, and water associated with making and using that product.

Several organizations have proposed how an LCA should be conducted. Organizations such as the International Organization for Standardization (ISO, www.ISO.org), the Society of Environmental Toxicology and Chemistry (SETAC, www.SETAC.org), and the United States Environmental Protection Agency (www.EPA.gov) have documented standard procedures for conducting an LCA. These procedures are generally consistent with each other. What these standards have in common is that they are scientific, explained in detail, and repeatable.

The usefulness of an LCA or LCI depends on where the boundaries of a product are drawn. A common approach is to consider all of the environmental flows from cradle-to-grave. A system boundary for a precast concrete operation would look like the diagram on the next page.

Note that the boundary does not include upstream profiles of fuel, electricity, water, or supplementary cementitious materials. It also does not include form preparation, placing the concrete in the formwork, curing, and stripping. A complete precast concrete LCI would include these steps.



An upstream profile can be considered as a separate LCI that is itself an ingredient to a product. For example, the upstream profile of cement is essentially an LCI of cement, which can be imported into an LCI of concrete. The LCI of concrete can then be imported into an LCI of a product, such as an office building.

To obtain the most useful information from an LCI, precast concrete should be considered in the context of its end use. For example, in a building, the environmental impact of the building materials is usually dwarfed by the environmental impacts associated with building operations such as heating, ventilating, cooling, and lighting.

Life-cycle inventories of materials generally do not consider embodied energy and emissions associated with construction of manufacturing-plant equipment and buildings, nor the heating and cooling of such buildings. This is generally acceptable if their materials, embodied energy, and associated emissions account for less than 1% of those in the process being studied. Guidelines established by the Society of Environmental Toxicology and Chemistry indicate that inputs to a process do not need to be included in an LCI if:

- They are less than 1% of the total mass of the processed materials or product.
- They do not contribute significantly to a toxic emission.
- They do not have a significant associated energy consumption.

(For more on this aspect, see Reference 3.)

Precast Concrete LCI

The data gathered in an LCI is voluminous by nature and does not lend itself well to concise summaries; that is the function of the LCA. The data in typical LCI reports often are grouped into three broad categories: materials, energy, and emissions. These LCI data do not include the upstream profiles of supplementary cementitious materials (such as fly ash, silica fume, etc.) or energy sources (such as fuel and electricity).

The embodied energy of concrete increases in direct proportion to its cement content. Therefore, the embodied energy of concrete is sensitive to the cement content of the mix and to the assumptions about LCI energy data in cement manufacturing.

Replacing cement with supplementary cementitious materials, such as slag cement or silica fume, has the effect of lowering the embodied energy of the concrete. Fly ash, slag cement, and silica fume do not contribute to the energy and emissions embodied in the concrete (except for the small energy contributions due to slag granulation/grinding, which is included). These products are recovered materials from industrial processes (also called post-industrial recycled materials) and, if not used in concrete, would use up valuable landfill space.

For instance, with a 20% replacement of fly ash for portland cement in a 3000-psi (20 MPa) mixture, embodied energy changes from 1.2 to 1.1 MBtu/yd^3 (1.7 to 1.5 GJ/m^3), a 10% reduction. With a 50% slag-cement replace-ment for portland cement in a 5,000-psi (35 MPa) mixture, embodied energy changes from 2.3 to 1.5 GJ/m^3 (1.7 to 1.1 MBtu/yd^3), a 34% reduction.

Fly ash or slag cement replacement of portland cement also can significantly reduce embodied emissions. For instance, a 20% substitution of fly ash for portland cement in a 3000-psi (20 MPa) mixture results in a 17% reduction in carbon dioxide emissions. A 45% carbon-dioxide-emissions reduction is achievable with 50% substitution of slag for portland cement in a 7500-psi (50 MPa) precast concrete mixture.

Embodied energy of reinforcing steel used in concrete is relatively small because it represents only about 1% of the weight in a unit of concrete, and it is manufactured mostly from recycled scrap metal. Reinforcing steel has over 90% recycled content, according to the Concrete Reinforcing Steel Institute (www.crsi.org) The process for manufacturing reinforcing bar from recycled steel uses significant energy and should be considered if the reinforcing bar content is more than 1% of the weight of the concrete.

It is assumed that, at a typical site and in a precast concrete plant, concrete-production formwork is reused a number of times through the repetitious nature of work, so its contribution to an LCI or LCA is negligible. Steel and wood formwork is generally recycled at the end of its useful life (see Reference 4).

References:

1. Chapter 5, Section 5.4.3, “Life Cycle,” MNL-122-07: *PCI Architectural Precast Concrete Manual, Third Edition.*
2. Chapter 5, Section 5.4.3.1, “Life Cycle Cost and Service Life,” MNL-122-07: *PCI Architectural Precast Concrete Manual, Third Edition.*
3. Chapter 5, Section 5.4.3.2, “Environmental Life Cycle Inventory and Life Cycle Assessment,” MNL-122-07: *PCI Architectural Precast Concrete Manual, Third Edition.*
4. Chapter 5, Section 5.4.3.3, “Concrete and Concrete Products LCI,” MNL-122-07: *PCI Architectural Precast Concrete Manual, Third Edition.*

Resources:

MNL-122-07: *PCI Architectural Precast Concrete Manual, Third Edition.*

CHAPTER THREE e.

Sustainability & LEED Considerations

Precast concrete components can aid designers in achieving sustainable designs and in meeting standardized requirements for environmentally friendly designs. Sustainability has become a watchword for owners and architects when designing new buildings, intermingled with terms such as "environmental friendliness" and "green building."

In general, sustainability is considered to mean development that meets present needs without compromising the ability to meet the needs of future generations. The goal is to use building materials and energy resources in ways that will minimize their depletion or not restrict their ability to be used by future generations.

Today's approach extends beyond the ability to renew or recycle resources to examine the embodied energy required to make use of that material. This accounting practice encompasses all the energy necessary to manufacture, deliver, and install the product, including fuel to extract materials, finish them, and transport them to the site. Even so, the concept also balances environmental impact with cost-effectiveness.

While other building materials may have to alter their configurations or properties to be applicable to sustainable structures, precast concrete's inherent composition allows it to naturally achieve sustainability. It contributes by incorporating integrated design, using materials efficiently, and reducing construction waste, site disturbance, and noise.

The information in this chapter, which discusses sustainable concepts as they apply to precast concrete, is condensed and edited from Chapter 5, Section 5.4, "Sustainability," in PCI's *Architectural Precast Concrete Manual, Third Edition* (MNL-122-07). Additional resources pertaining to precast's role in designing a sustainable building can be found at the end of the chapter.

INTEGRATED DESIGN

Precast concrete components play a key role in maximizing benefits from integrated-design strategies. Integrated design, also called the holistic or whole-building approach, focuses on all of the building's materials, systems, and design from the perspective of all project team members and tenants.

Decisions are based on the combination of energy efficiency, cost, durability (or service life), space flexibility, environmental impact, and quality of life. Choices in one area impact other areas, requiring all systems to be considered together to maximize efficiency and minimize redundancies or interference.

Integrated design requires coordinating the architectural, structural, and mechanical designs early in the schematic-design phases to evaluate system interactions and decide which beneficial interactions are essential for project success. For example, a well-insulated building with minimal windows facing east and west requires less heating and air-conditioning. That reduction, in turn, could result in fewer ducts or the elimination of registers along the building's perimeter.

Integrated design consists of eight key components. Requests for proposals and contracts should clearly describe sustainability requirements and project documentation. The eight components are:

1. Emphasize the integrated process.
2. Consider the building as a whole—often interactive, often multi-functional.
3. Focus on the life cycle.
4. Have disciplines work together as a team from the start.
5. Conduct relevant assessments to help determine requirements and set goals.
6. Develop tailored solutions that yield multiple benefits while meeting requirements and goals.
7. Evaluate solutions.
8. Ensure requirements and goals are met.

The U.S. Department of Transportation facility in Lakewood, Colo., used an all-precast concrete structure to help it achieve LEED Silver Certification. Design Architect: Oz Architecture; Architect/engineer: Opus Architects & Engineers Inc.; Photo: Oz Architecture.

Some of the primary ways that precast concrete components can help include:

- Precast concrete walls act as thermal storage to delay and reduce peak thermal loads.
- Precast concrete walls used with insulation provide energy benefits that exceed the benefits of mass or insulation used alone in most climates.
- Precast concrete sandwich wall panels used as an interior surface can save material by eliminating the need for framing and drywall.
- Hollow-core panels used as ducts can save material and energy by eliminating ductwork and charging the thermal mass of the panel.
- Precast concrete walls can be designed to be disassembled for building-function changes, saving material and extending the service life of the panels.
- Precast concrete's durability creates a long life cycle and low maintenance, which creates less need for replacement and maintenance during the building's life.
- As a plant-cast product manufactured under tight quality controls, precast concrete eliminates any construction waste and minimizes transportation and disposal costs.

In addition, a major tenet of an integrated-design strategy embracing sustainable concepts is to focus on three ways to minimize the material used in the project:

1. **Reduce the amount of material used and the toxicity of waste materials.** Precast concrete can be designed to optimize or lessen the amount of concrete used. Industrial wastes such as fly ash, slag cement, and silica fume can be incorporated into the mix, reducing the amount of cement. As a manufactured product created under controlled conditions in the plant, precast concrete generates low amounts of waste, and the waste generated has low toxicity. It is generally assumed that 2% of the concrete at the plant is waste, but because it is generated at the plant, 95% of the waste is used beneficially elsewhere.

2. **Reuse and repair products.** Precast concrete panels can be reused when buildings are expanded. Concrete pieces from demolished structures also can be reused, such as protection for shorelines. Because the precast process is self-contained, formwork and finishing materials are reused. Wood or fiberglass forms can generally be used 40 to 50 times without major maintenance, while concrete and steel forms have practically unlimited service lives.

3. **Recycle and use products with recycled content.** Concrete can be recycled as fill or road base. Wood and steel forms are recycled when they become worn or obsolete. Virtually all reinforcing steel is made from recycled steel. Many cement plants burn waste-derived fuels such as spent solvents, used oils, and tires.

LEED Rating System

Precast concrete can help buildings in a variety of ways to achieve the standards created by the LEED building-rating system. LEED is a voluntary, consensus-based national standard for developing high-performance, sustainable buildings. Administered by the U.S. Green Building Council, LEED-NC applies to new construction and major renovation projects and covers commercial and institutional projects as well as high-rise residential new construction and major renovation projects.

The system uses points to create a framework for assessing building performance and meeting sustainability goals. Points are awarded when a specific intent is met, and a building is LEED certified if it obtains at least 26 points. Additional silver, gold, and platinum levels of ratings are awarded for at least 33, 39, and 52 points, respectively. The points are grouped into five categories:

1. Sustainable Sites
2. Water Efficiency
3. Energy & Atmosphere
4. Materials & Resources
5. Indoor Environmental Quality

Appropriate use of precast concrete components can help a building earn up to 27 points, one more than is required for LEED certification. Precast concrete can help meet minimum energy requirements, optimize energy performance, and increase the life of a building. The constituents of concrete can be made from recycled materials, and concrete itself can also be recycled. The materials are usually available locally.

These attributes of concrete, recognized in the LEED rating system, can help lessen a building's impact on the natural environment. Points applicable to precast concrete are summarized in the accompanying table. The USGBC website (www.usgbc.org) contains a downloadable "letter template" that greatly simplifies documentation requirements

Total-precast concrete structure aids office design by offering "green" qualities, including close proximity, energy efficiency, reliability, and minimal construction waste.

CH2M Hill World Headquarters, Englewood, Colo.; Architect: Barber Architecture, Denver, Colo.; Photos: Rocky Mountain Prestress.

LEED* Project Checklist: Precast Concrete Potential Points

LEED CATEGORY	CREDIT OR PREREQUISITE	POINTS AVAILABLE
Sustainable Sites	Credit 5.1: Site Development, Protect or Restore Habitat	1
Sustainable Sites	Credit 5.2: Site Development, Maximize Open Space	1
Sustainable Sites	Credit 7.1: Heat Island Effect, Non-Roof	1
Energy and Atmosphere	Prerequisite 2: Minimum Energy Performance	—
Energy and Atmosphere	Credit 1: Optimize Energy Performance	1-10
Materials and Resources	Credit 1.1: Building Reuse, Maintain 75% of Existing Shell	1
Materials and Resources	Credit 1.2: Building Reuse, Maintain 95% of Existing Shell	1
Materials and Resources	Credit 2.1: Construction Waste Management, divert 50% by weight or volume	1
Materials and Resources	Credit 2.2: Construction Waste Management, divert 75% by weight or volume	1
Materials and Resources	Credit 4.1: Recycled Content, the post-consumer recycled content plus one-half of the pre-consumer content constitutes at least 10% (based on cost) of the total value of the materials in the project	1
Materials and Resources	Credit 4.2: Recycled Content, the post-consumer recycled content plus one-half of the pre-consumer content constitutes at least 20% (based on cost) of the total value of the materials in the project	1
Materials and Resources	Credit 5.1: Local/Regional Materials, Use a minimum of 10% (based on cost) of the total materials value	1
Materials and Resources	Credit 5.2: Local/Regional Materials, Use a minimum of 20% (based on cost) of the total materials value	1
Indoor Environmental Quality	Credit 3.1: Construction Indoor Air Quality Management Plan, during construction	1
Innovation and Design Process	Credit 1.1: Use of high volume supplementary cementitious materials. Apply for other credits demonstrating exceptional performance	1†
Innovation and Design Process	Credits 1.2: Apply for other credits demonstrating exceptional performance	1†
Innovation and Design Process	Credits 1.3: Apply for other credits demonstrating exceptional performance	1†
Innovation and Design Process	Credits 1.4: Apply for other credits demonstrating exceptional performance	1†
Innovation and Design Process	Credit 2.1: LEED Accredited Professional	1
	PROJECT TOTALS	**23**

*LEED: Leadership in Energy and Environmental Design.

† Up to 4 additional points can be earned, must be submitted and approved (not included in total).

Note: Scoring System: Certified, 26-32 points; Silver, 33-38 points; Gold, 39-51 points; and Platinum, 52-69 points.

PRECAST CONCRETE ATTRIBUTES APPLIED TO LEED CERTIFICATION

The attributes and capabilities of precast concrete that help meet LEED certification vary by the intent of each category. The key applications center on the following attributes:

Durability

Durability of the original structure represents a key factor in building reuse. Precast concrete panels provide a long service life due to their durable and low-maintenance concrete surfaces. A precast concrete shell can be left in place when the building interior is renovated. Yearly maintenance should include inspection and, if necessary, repair of joint material.

Modular and sandwich-panel construction with precast concrete exterior and interior walls provides long-term durability inside and out. Precast concrete construction creates the opportunity to refurbish the building if its use or function changes rather than tearing it down to start anew.

These characteristics of precast concrete make it sustainable in two ways:

1. It avoids contributing solid waste to landfills.
2. It reduces the depletion of natural resources and production of air and water pollution caused by new construction.

Mitigating the Urban Heat-Island Effect

Precast concrete provides reflective surfaces that minimize the urban heat-island effect. Cities and urban areas are 3 °F to 8 °F warmer than surrounding areas due to buildings and pavements taking the place of vegetation. Trees provide shade that reduce temperatures at the surface and also create transpiration and evaporation that cool the surfaces and air surrounding them.

Urban heat islands result primarily from solar radiation being absorbed by horizontal surfaces such as roofs, pavements, parking lots, driveways, and walkways. Vertical surfaces, such as the sides of buildings, also contribute. The ability of a material to reflect solar heat is called albedo, and the higher the material's albedo, the better it reflects. High albedo can reduce the heat-island effect, save energy by reducing the demand for air conditioning, and improve air quality.

Concrete has a relatively high albedo. Traditional portland-cement concrete generally has an albedo or solar reflectance of approximately 0.4. The solar reflectance of new concrete is greater when the surface reflectance of the sand and cementitious materials in the concrete are greater. Surface finishing techniques also have an effect, with smoother surfaces generally having a higher albedo. Lighter or white colors also increase solar reflectance.

Typical Albedos for Selected Building Products

Material	Albedo Range
Alphalt	.05-.20
Roofing tile	.10-.35
Stone	.20-.35
New concrete	.35-.40
Colored metal roofs	.55-.66
Cool roofs (with reflective membrane)	.85
Snow	.75-.95

Source: U.S. Environmental Protection Agency (www.epa.gov) and ESPERE-ENC (Environmental Science Published for Everybody Round the Earth-Educational Network on Climate)

Moisture in concrete helps to cool the surface by evaporation, too. Concrete, when placed, has a moisture content of 100% relative humidity. The concrete surface gradually dries over a period of one to two years, until it reaches equilibrium with its surroundings. Concrete surfaces exposed to rain and snow will continue to become wet and dry. This moisture helps cool the concrete by evaporation whenever the temperature and relative humidity of the air are greater than that just beneath the concrete surface.

The thermal mass of concrete delays the time it takes for a surface to heat up, but it also delays the time to cool off. For example, a white roof will get warm faster than concrete during the day, but will also cool off faster at night. Concrete surfaces are often warmer than air temperatures in the evening hours.

Concrete's albedo and thermal mass will help mitigate heat-island effects during the day but may contribute to the nocturnal heat island effect. Designers should try to use concrete to mitigate heat islands while keeping evening temperatures as cool as possible.

Precast Concrete Production

The production of precast concrete has many environmental benefits, including:

- Less material is required because precise mixture proportions and tighter tolerances are achieved.
- Optimal insulation levels can be incorporated into precast concrete sandwich wall panels.
- Waste materials are more likely to be recycled because concrete production is in one location.
- Gray water is often recycled into future mixtures.

- Hardened concrete is recycled (about 5% to 20% of aggregate in precast concrete can be recycled concrete).
- Steel forms and other materials are reused.
- Less dust and waste are created at the construction site because only needed precast concrete elements are delivered.
- There is no debris from formwork and associated fasteners.
- Fewer trucks and less time are required for construction because concrete is made offsite, which is particularly beneficial in urban areas where minimal traffic disruption is critical.
- Precast concrete units are normally large components, so greater portions of the building are completed with each activity.
- Less noise is generated at the construction site because concrete is made offsite.
- Less concrete generally is used in precast buildings compared with other concrete buildings because of the optimization of materials. A properly designed precast concrete system will result in smaller structural members, longer spans, and less material used onsite. This creates economic and environmental savings.

Precast concrete components can provide the building structure as well as the interior and exterior finishes. Structurally efficient columns, beams, and slabs can be left exposed with natural finishes. Interior and exterior concrete walls offer a wide range of profile, texture, and color options that require little or no additional treatment to achieve aesthetically pleasing results.

Constituent Materials

Concrete contributes to a sustainable environment because it does not use scarce resources. It consists of only a few ingredients, primarily cement, water, large and small aggregates, and admixtures, all of which are abundant locally.

Portland cement is made by heating common minerals (primarily crushed limestone, clay, iron ore, and sand) to a white-hot mixture to form clinker. This intermediate product is ground with a small amount of gypsum to form a fine, gray powder. To trigger the necessary chemical reactions in the kiln, these raw materials must reach a temperature of about 2700 °F, the temperature of molten iron. Although portland cement is energy intensive, the U.S. cement industry has reduced energy usage per ton of cement by 35% since 1972.

Aggregates, which comprise about 85% of concrete, generally consist of materials that require low levels of energy to produce, comprising local, naturally occurring sand and stone. Limestone and clay needed to manufacture cement also are prevalent. Limestone and aggregate quarries often are reused. While quarrying is intense, it is closely contained and temporary.

Three types of industrial by-products, or pozzolans, are used to replace portland cement in concrete to reduce the energy and CO_2 impacts of cement in concrete. If not used in concrete, these pozzolans would use valuable landfill space. These admixtures are:

1. **Fly ash**, a by-product of the combustion of pulverized coal in electric power generating plants. It can replace up to 25% of the cement used in precast concrete.
2. **Slag cement**, made from iron blast-furnace slag. It can replace up to 60% of the cement used in precast concrete.
3. **Silica fume**, a by-product from the electric arc furnace used in the production of silicon or ferrosilicon alloy. It can replace up to 7% of the cement used in precast concrete.

Because the cementitious content of concrete accounts for only about 15% of the material's total, these pozzolans typically comprise only 2% to 5% of the overall concrete material in buildings. However, their use can have a significant effect on the environmental impact of concrete: When slag cement replaces 50% of the portland cement in a 7500-psi concrete, greenhouse-gas emissions per cubic yard of concrete are reduced by 45%.

The environmental attributes of concrete can be further improved by using aggregates derived from industrial waste or using recycled concrete as aggregates. Blast-furnace slag is a lightweight aggregate with a long history of use in the concrete industry. Recycled concrete also can be used as aggregate in new concrete, particularly the coarse portion.

Admixtures provide enhancing qualities in concrete but are used in such small quantities that they do not adversely affect the environment. Likewise, color pigments used to provide decorative colors in precast concrete generally do not contribute to environmental calculations, although some may contain trace amounts of heavy-metals.

The use of local materials reduces the transportation needs for heavy building materials, along with the associated energy and emissions. Most precast concrete plants are within 200 miles of a building site. The cement, aggregates, and reinforcing steel used to fabricate precast concrete components, along with the raw materials used to manufacture cement, are usually obtained or extracted from sources within 200 miles of the precast concrete plant.

Precast concrete elements are usually shipped efficiently because of their large, often repetitive sizes and the ability to plan their shipment during the normal course of the project.

Energy Conservation

Energy conservation is a key tenet of sustainability. About 90% of the energy used during a building's life is attributed to heating, cooling, and other utilities. The remaining 10% is attributed to manufacturing materials, construction, maintenance, replacement of components, and demolition.

Precast concrete's inherent capabilities to provide energy efficiency rely on the high thermal mass of the material, which benefits exterior wall applications. Precast concrete walls provide benefits because they:

- Delay or reduce peak loads.
- Reduce total loads in many climates and locations.
- Work well regardless of the placement of mass.

Precast's thermal mass works best in commercial applications by delaying the peak summer load, which generally occurs around 3:00 p.m. The high mass also can be applied to smaller residential applications. The approach works most efficiently when mass is exposed on the inside surface.

Precast concrete's high thermal mass may help shift the peak hour of electric demand for air conditioning to a later hour and help reduce time-of-use charges. Nighttime ventilation can be used to cool thermal mass that has been warmed during the day. Local outdoor humidity levels influence the effectiveness of nighttime ventilation strategies. These strategies can help to reduce the overall load in many climates.

Mass works well on the inside surfaces by absorbing the heat gains generated by people and equipment indoors. Interior mass from interior walls, floors, and ceilings will help moderate room temperatures and reduce peak energy use.

Thermal mass is most effective in locations and seasons where the daily outdoor temperature rises above and falls below the building's balance-point temperature. The balance-point temperature is the outdoor temperature below which heating will be required. It is less than room temperature, generally between 50 °F and 60 °F, at the point where internal heat gains approximately equal the heat losses through the building envelope. In many climates, buildings with thermal mass have lower energy consumption than non-massive buildings with walls of similar thermal resistance; heating and cooling needs can be met with smaller equipment sizes.

Light-colored precast concrete will reduce energy costs associated with indoor and outdoor lighting. The more reflective surfaces will reduce the amount of fixtures and lighting required.

To maximize the effectiveness of the insulation used with precast concrete panels, thermal bridges (disruptions of insulation between two layers of concrete) should be minimized or avoided. Fiberglass or epoxy-coated, carbon fiber composite fasteners or thermal breaks offer the best approach, as they will minimize thermal bridges. Concrete thermal bridges may occur at the bottom and the top of concrete panels. Metal thermal bridges may occur as fasteners that penetrate insulation to connect concrete layers.

Concrete contains low to negligible volatile organic compounds (VOC). These compounds degrade indoor air quality when they off gas from new products such as interior finishings, carpet ,and furniture. Manufactured wood products such as laminate, particleboard, hardboard siding, and treated wood can also lead to off gassing. In addition, VOCs combine with other chemicals in the air to form ground-level ozone.

Polished concrete floors do not require carpeting. Exposed concrete walls do not require finishing materials. The VOCs in concrete construction can be reduced further by using low-VOC materials for form-release agents, curing compounds, damp-proofing materials, wall and floor coatings and primers, membranes, sealers, and water repellants.

Precast concrete components can further help meet LEED standards for indoor air quality because they are delivered to the site in modules that do not require fabrication, processing, or cutting at the construction site, thereby reducing dust and airborne contaminants on site. Concrete is not damaged by moisture and does not provide nutrients for mold growth.

Precast concrete panels can be reused when buildings are expanded, and precast concrete can be recycled as road base or fill at the end of its useful life. Concrete pieces from demolished structures can be reused to protect shorelines. Most concrete from demolition in urban areas is recycled and not placed in landfills.

The concrete industry has LEED-experienced professionals available to assist teams with concrete applications and help maximize points for concrete. An additional point is available if a principal participant of the project team is a LEED-accredited professional.

Resources:

DN-15 *Designer's Notebook: Energy Conservation & Condensation Control*.

Ascent:

"Best Justice Facility: Fresno Courthouse & Federal Building," *Ascent*, Fall 2006, p. 30.

"DOT Project Shows LEEDership," *Ascent*, Winter 2006, pp. 32-35.

"Precast Helps Attain LEED Certification," *Ascent*; Winter 2005, pp. 18-23.

"Precast Helps Projects Attain LEED Certification," *Ascent*; Summer 2004, pp. 18-22.

PCI Journal:

"Achieving Sustainability with Precast Concrete," *PCI Journal*, January-February 2006, pp. 42-61.

"Analytical Investigation of Thermal Performance of Precast Concrete Three-Wythe Sandwich Wall Panels," *PCI Journal*; July-August 2004, pp. 88-101.

"Some Aspects of Sustainability," *PCI Journal*, January-February 2006, p. 75.

"State-of-the-Art of Precast/Prestressed Sandwich Wall Panels," *PCI Journal*; March-April 1997, pp. 92-134.

"U.S. Department of Transportation Facility, Lakewood, Colo.," *PCI Journal*, January-February 2006, pp. 76-81.

References:

Chapter 5, Section 5.4, "Sustainability," MNL-122-07: *PCI Architectural Precast Concrete Manual, Third Edition*.

CHAPTER THREE

f.

Health & Indoor Air Quality

Building users have growing concerns about having a healthy environment in which to work, shop, play, and live. The damage that can be wrought by mold and the lack of fresh air within a structure continues to gain awareness, making designers place more emphasis on controlling these factors in their structures. Mold damage has ruined countless projects and has been directly or indirectly linked to severe illness and harm to individuals.

A side aspect to this problem for designers is that mold problems have clogged the court system with more than $300 million annually in litigation as well as produced a 300% increase each year in the number of lawsuits filed nationwide. Remediating mold growth also requires expensive treatments that disrupt the building's operation and pose burdens on operating budgets.

Proper design and production techniques can help prevent mold proliferation as well as reduce moisture damage and water migration. The proper design of building envelopes with the correct construction materials is a key way to reduce the presence and potential damage from mold (see Reference 1).

Orville L. Freeman Office Building and Laboratory, St. Paul, Minn.; Architect: HGA.

Mold requires four conditions to thrive: mold spores, organic matter for food, moisture, and optimal temperatures (40 to 100 °F).

There is no way to eliminate all mold in the interior environment, as it exists throughout the natural world. Treatment of materials with chemicals may reduce the potential for mold but can not eradicate it. The careful attention to the building envelope, the choice of materials, and control of moisture penetration can reduce harmful mold's success in establishing itself and growing.

Precast concrete aids in controlling mold growth for a number of reasons:

- **It is not an organic material.** While concrete can accumulate dirt and debris, which can breed mold, its durability allows it to be cleaned in place rather than removed for remediation, as must happen with many other organic construction materials.

- **Its production is controlled away from moisture.** Unless properly designed and constructed, the building site can permit excessive moisture in either surface, underground water, outside humid air, or rain into openings like doors, windows, ventilation ducts, or shafts that pull outside air in the buildings. Precast concrete is produced in a controlled and protected environment in a process that resists moisture intrusion. By delivering the components to the site as needed, they are exposed to the environment for a shorter period of time (see Reference 2).

- **Precast concrete's speed provides interior protection quicker.** The use of precast concrete systems to construct building envelopes also allows the structure to be completed faster, leaving it exposed to humidity and moisture for a shorter time period. This is particularly vital for the installation of the HVAC system, which is one of the more common entrance paths for mold formation. During the "exposed" phase of the construction process, mold spores can come to rest on building materials and components, whether installed or simply stored. If water is added from any natural or other source, the spores may be able to begin to grow.

- **It can be cleaned easily.** Concrete can be cleaned of mold and dust spores, making them ideal substrates for controlling mold growth. The cleaning can be accomplished on precast concrete components by pressure washing, which rids the surface of any food source for mold that may have lodged there. In addition, the site's natural ventilation will normally dry out concrete and steel, eliminating moisture as a source of growth (see Reference 3).

- **Precast concrete provides fewer entry points.** Because of its panelized construction, fewer points of potential moisture penetration exist with precast concrete panels. This helps control moisture and eliminate the possibility for mold growth in water that penetrates the walls. Maintenance needs for precast concrete panels are also minimal, with panels only requiring caulking every 15 to 20 years to maintain their reliability. This limits the need to budget for repairs in annual maintenance budgets and reduces the potential for lapses to allow problems to develop.

- **It ensures mold growth isn't exacerbated by changes in the interior environment.** Because precast concrete panels eliminate worries about moisture penetration, administrators can reduce HVAC usage when a building, especially seasonal structures such as schools, are unoccupied for long periods and not worry that they are risking mold growth or creating bad indoor air quality (see Reference 4).

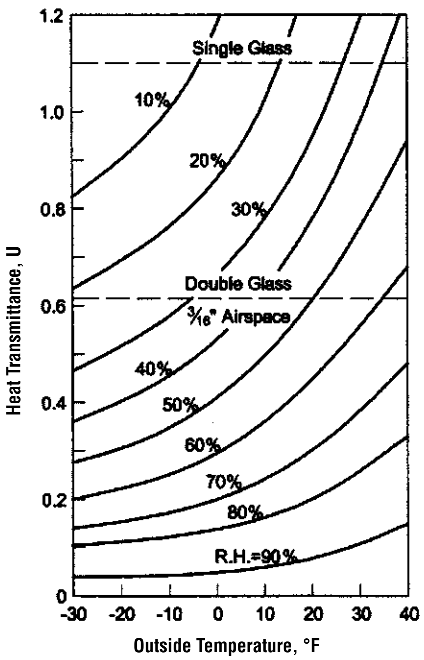
AIR, VAPOR BARRIERS REQUIRED

Controlling condensation in a building with a precast concrete façade, as with any material, requires an air barrier and a vapor barrier, although they often consist of a single material that can provide both functions. The principle function of the air barrier is to stop outside air from entering the building through the walls, windows, or roof, and inside air from exfiltrating through the building envelope to the outside environment.

The principal function of a vapor retarder made of low-permeability materials is to stop or retard the passage of moisture as it diffuses through the assembly of materials in a wall. Vapor-diffusion control is easy to achieve and is primarily a function of the water-vapor diffusion resistance of the chosen materials and their position within the building-envelope assembly. The vapor retarder should be clearly identified by the designer and be clearly identifiable by the general contractor (see Reference 5).

Precast concrete construction supports the scientific community's maxim to prevent or inhibit mold formation rather than attempt remediation of fungi in indoor environments.

In addition, precast concrete panels have no outgassing that can cause deteriorated air quality. This has become a critical component in recent years as the need to enhance energy efficiency has tightened the "breathability" of buildings, preventing air from infiltrating and exfiltrating, which retains existing particulates in the air. Precast concrete will not add to this outgassing that comes from volatile organic compounds and new materials brought into the structure (see Reference 6).



References:

1. "Mold White Paper," produced for the Precast/Prestressed Concrete Institute; April 2005, p. 1.
2. "Mold White Paper," produced for the Precast/Prestressed Concrete Institute; April 2005, p. 2.
3. "Mold White Paper," produced for the Precast/Prestressed Concrete Institute; April 2005, p. 3.
4. MK-34-03: Precast Concrete Makes the Grade For K-12 School Facilities (12 pp.).
5. Chapter 5, Section 5.3.6, "Condensation Control," MNL-122-07: *PCI Architectural Precast Concrete Manual, Third Edition.*
6. "Mold White Paper," produced for the Precast/Prestressed Concrete Institute; April 2005, p. 4.

Resources:

Chapter 5, Section 5.3.6, "Condensation Control," MNL-122-07: *PCI Architectural Precast Concrete Manual, Third Edition.*

Chapter 9.1.7.1, "Air Barriers," PCI MNL-120-04: *PCI Design Handbook, Sixth Edition.*

Chapter 9.1.7.2, "Vapor Retarders," PCI MNL-120-04: *PCI Design Handbook, Sixth Edition.*

"Mold White Paper," produced for the Precast/Prestressed Concrete Institute; April 2005, p. 4.

MK-34-03: *Precast Concrete Makes the Grade For K-12 School Facilities.*

CHAPTER THREE

g.

Acoustics

Inhabited spaces should be acoustically designed to provide a satisfactory environment in which desired sounds are heard clearly and unwanted sounds are isolated or absorbed. Under most conditions, the architect or engineer can determine the acoustical needs of the space and then design the building to satisfy those needs.

Good acoustical design uses absorptive and reflective surfaces, sound barriers, and vibration isolators. Sound is isolated from rooms where it is not wanted by selected wall and floor-ceiling constructions. Vibration generated by mechanical equipment must be isolated from the structural frame of the building.

The Juanita K. Hammons Hall for the Performing Arts, Springfield, Mo.; Architect: Pelham-Phillips-Hagerman; and Butler, Rosenbury & Partners (joint venture); Photos: Pelham-Phillips-Hagerman.

For buildings that require more sophisticated acoustical analysis, such as churches, concert halls, or auditoriums, it may be desirable to review the needs with an acoustical design consultant (see Reference 1).

The ability of a barrier to reduce the intensity of airborne sound is commonly designated by its Sounds Transmission Class (STC). Precast concrete walls, floors, and roofs usually do not need additional treatment to provide adequate sound insulation (see Reference 2).

Even when airborne sounds are adequately controlled, there can be severe impact noise problems. Footsteps, dropped objects, slammed doors, and plumbing generate impact noise. For performance specifications, the Impact Insulation Class (IIC) is used to measure this sound. In general, thickness or unit weight of concrete does not greatly affect the transmission of impact sounds. Structural concrete floors, combined with resilient materials such as carpeting, effectively control impact sound (see Reference 3).

Often, acoustical control is specified as to the minimum insulation values of the dividing partition system. Local building codes, lending institutions and the Department of Housing & Urban Development (HUD) list both airborne, STC and IIC values for different living environments:

HUD Recommendations for STC and IIC

Location	STC	IIC
Between living units	45	45
Between living units and public spaces	50	50

Source: Table 9.2.7.1, MNL-120-04: PCI Design Handbook, Sixth Edition

Other community ordinances can be more specific, listing the sound-insulation criteria with relation to particular ambient environments. Once objectives are established, the designer should refer to available data and select the system that best meets the requirements. In general, concrete systems have superior properties and can, with minimal effort, comply with these criteria (see Reference 4).

SOUND ABSORPTION VS. SOUND INSULATION

Designers must recognize that the basic mechanisms of sound absorption and sound insulation are quite different. Designing for sound insulation is usually considerably more complicated than designing for sound absorption. The former involves reductions of sound levels, which are of greater orders of magnitude than can be achieved by absorption. These large reductions of sound level from space to space can be achieved only by continuous, impervious barriers. It also may be necessary to introduce resilient layers of discontinuities into the barrier.

Sound-absorbing materials and sound-insulating materials are used for different purposes. For instance, an 8-in. concrete wall will not provide much sound absorption, while a porous, lightweight material that may be applied for sound absorption to room surfaces will not provide high sound insulation (see Reference 5).

SOUND-TRANSMISSION LOSS AND SOUND ABSORPTION

Sound-transmission loss measurements are made at 16 frequencies at one-third octave intervals covering the range from 125 to 4000 Hz. Airborne sound reaching a wall, floor, or ceiling produces vibrations in the wall that are radiated with reduced intensity on the other side. Airborne sound-transmission loss in wall assemblies is a function of their weight, stiffness, and vibration-damping characteristics.

Weight is concrete's best asset when it is used as a sound insulator. For sections of similar design but different weights, the STC increases approximately 6 units for each doubling of weight. This is shown in Fig. 1, which describes sound transmission class as a function of weight based on experimental data.

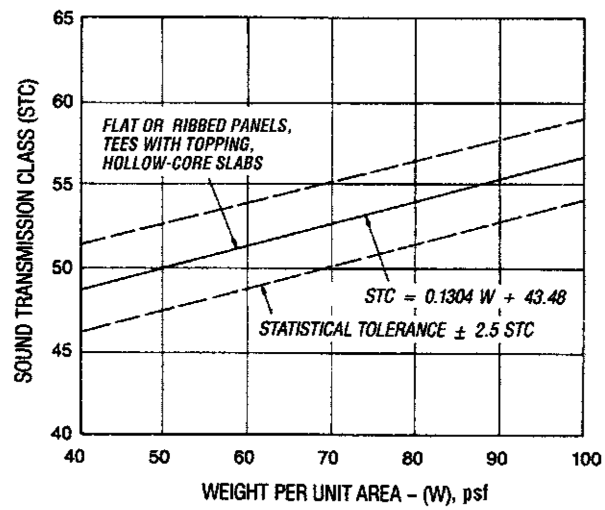


Fig. 1: Sound transmission class as a function of weight of floor or wall.

Precast concrete walls usually do not need additional treatments to provide adequate sound insulation. If desired, greater sound insulation can be obtained by using resiliently attached layers of gypsum board or other building materials. The increased transmission loss occurs because the energy flow path is increased to include a dissipative air column and additional mass (see Reference 6).

A dense, nonporous concrete surface typically absorbs 1% to 2% of incidental sound. Where additional sound absorption is desired, a coating of acoustical material can be spray applied, acoustical tile can be applied with adhesive, or an acoustical ceiling can be suspended. Most of the spray-applied, fire-retardant materials used to increase the fire resistance of precast concrete and other floor-ceiling systems can also be used to absorb sound (see Reference 7).

COMPOSITE WALL CONSIDERATIONS

Windows and doors are often the weak link in an otherwise effective sound barrier. Minimal effects on sound-transmission loss will be achieved in most cases by proper selection of glass. The control of sound transmission through windows requires large cavities between layers (multiple glazing), heavy layers (thicker glass), and a reduction of the structural connection between layers (separate frames and sashes for inner and outer layers).

These penetrations should be designed to be as airtight as possible. Fixed windows usually provide much better sound-transmission control than operable windows. The sound-transmission loss through a door depends on the material and construction of the door as well as on the effectiveness of the seal between the door and its frame.

There is a mass law dependence of STC on weight (psf) for both wood and steel doors. The approximate relationships are:

- For steel doors: STC = 15 + 27 log W
- For wood doors: STC = 12 + 32 log W

In these relationships, W = weight of the door, psf. These relationships are purely empirical, and a large deviation can be expected for any given door.

For best results, the distances between adjacent door and window openings should be maximized, staggered when possible, and held to a minimum area. Minimizing openings allows the wall to retain the acoustical properties of the precast concrete. The design characteristics of the door or window systems must be analyzed prior to writing the project specification.

Such qualities as frame design, door construction, and glazing thickness are vital performance criteria. Installation procedures must be exact and care must be given to the framing of each opening. Gaskets, weatherstripping, and raised thresholds serve as both thermal and acoustical seals and are recommended (see Reference 8).

Alberta Lea High School, Alberta Lea, Minn.; Photo: ©Don F. Wong.

LEAKS AND FLANKING

A building section's performance with an otherwise adequate STC can be seriously reduced by a relatively small hole (or any other path) that allows sound to bypass the acoustical barrier. All noise that reaches a space by paths other than through the primary barrier is called flanking noise.

Common flanking paths are openings around doors or windows, electrical outlets, telephone and television connections, and pipe and duct penetrations. Suspended ceilings in rooms where walls do not extend from the ceiling to the roof or floor above also allow sound to travel to adjacent rooms by flanking.

Anticipation and prevention of leaks begins at the design stage. Flanking paths or gaps at the perimeters of interior precast concrete walls and floors are generally sealed during construction with grout or drypack. All openings around penetrations through walls or floors should be as small as possible and must be sealed airtight. The higher the required STC of the barrier, the greater the importance of sealing all openings.

Perimeter leakage commonly occurs at the intersection between an exterior cladding panel and a floor slab. It is of vital importance to seal this gap to retain the acoustical integrity of the system and provide the required fire stop between floors. One way to seal the gap is to place a mineral-wool blanket covered by sealant between the floor slab and the exterior wall.

Flanking paths can be minimized in three ways:

1. Interrupt the continuous flow of energy with dissimilar materials, such as with expansion or control joints or air gaps.
2. Increase the resistance to energy flow with floating floor systems, full-height or double partitions, and suspended ceilings.
3. Use primary barriers that are less subject to the creation of flanking paths. Although not easily quantified, an inverse relationship exists between the performance of an element as a primary barrier and its propensity to transmit flanking sound. The probability of existing flanking paths in a concrete structure is much less than in one of steel or wood framing.

If the acoustical design is balanced, the maximum amount of acoustical energy reaching a space via flanking should not equal the energy transmitted through the primary barriers. In exterior walls, the proper application of sealant and backup materials in the joints between units will not allow sound to flank the wall (see Reference 9).

References:

1. Chapter 9.2.2, "Acoustical Properties of Precast Concrete: General," MNL-120-04: *PCI Design Handbook, Sixth Edition.*
2. Chapter 9.2.4, "Sound Transmission Loss," MNL-120-04: *PCI Design Handbook, Sixth Edition.*
3. Chapter 9.2.5, "Impact Noise Reduction," MNL-120-04: *PCI Design Handbook, Sixth Edition.*
4. Chapter 9.2.7, "Establishment of Noise Insulation Objectives," MNL-120-04: *PCI Design Handbook, Sixth Edition.*
5. Chapter 9.2.3, "Acoustical Properties of Precast Concrete: Dealing with Sound Levels," MNL-120-04: *PCI Design Handbook, Sixth Edition.*
6. Chapter 5, Section 5.5.4, "Acoustical Properties: Sound Transmission Loss," MNL-122-07: *PCI Architectural Precast Concrete Manual, Third Edition.*
7. Chapter 5, Section 5.5.5, "Acoustical Properties: Absorption of Sound," MNL-122-07: *PCI Architectural Precast Concrete Manual, Second Edition.*
8. Chapter 5, Section 5.5.7, "Acoustical Properties: Composite Wall Considerations," MNL-122-07: *PCI Architectural Precast Concrete Manual, Third Edition.*
9. Chapter 5, Section 5.5.8, "Acoustical Properties: Leaks and Flanking," MNL-122-07: *PCI Architectural Precast Concrete Manual, Third Edition.*

Resources:

MNL-120-04: *PCI Design Handbook, Sixth Edition.*

MNL-122-07: *PCI Architectural Precast Concrete Manual, Third Edition.*

CHAPTER THREE

h.

Safety & Security

Providing a safe and secure structure for owners and users provides key challenges for designers. Integrating these critical functional aspects while meeting aesthetic goals and programmatic needs requires designers to remain up to date on new techniques and systems that can minimize the intrusion of security and safety elements in the overall plan. As security worries rise and Mother Nature continues to show her power, these concerns become key drivers for more clients.

Precast concrete designs can offer protection against fires, earthquakes, hurricanes, tornados, and explosive blasts when design and detailing are correctly applied. The requirements for achieving these goals must be taken into account as early in the design process as possible to maximize the effectiveness of precast concrete's capabilities against each of these issues.

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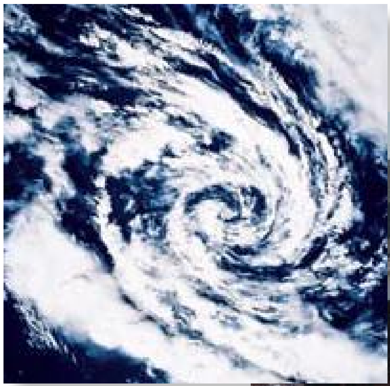


Photo: ©PhotoDisc

FIRE RESISTANCE

A key goal for the design team and the client is to protect the building from the multiple risks and losses caused by fire. A common misconception is that fire destroys by flames, which can be suppressed by sprinklers. In practice, this over-simplification can leave both property and human life vulnerable during a fire.

Among the goals that must be achieved when designing for fire safety are the following:

- **Contain high heat**, which can melt or ignite materials or kill in one breath.
- **Contain smoke that can blind**, choke, and ruin building components and contents. Smoke is often generated by the sprinkler suppression process, and it is unavoidable.
- **Contain toxic gas**, which is given off when plastics, synthetics, and chemicals burn. They can be deadly at any temperature.
- **Confine the fire event** to its place of origin and prevent it from spreading.
- **Reduce the fuel content** of the building by using non-combustible building materials whenever possible.
- **Avoid the potential for structural collapse** during the fire by protecting all structural framing elements that support the building.
- **Create a passive fire-protection strategy** for the building that will enable it to survive should arson, low water pressure, or a delayed fire-department response occur.
- **Divide the building** into several noncombustible compartments that will help achieve solutions for all the aforementioned hazards. This is the most important aspect of all.
- **Recognize that building codes** provide the minimum protection allowable and may not be enough to achieve the fire protection the building and its occupants will need. Each risk exposure requires a defense.

Photo: ©PhotoDisc.

Precast concrete provides noncombustible construction that can help contain a fire within minimal boundaries. As a separation wall, precast concrete helps to prevent a fire from spreading throughout a building or jumping between structures. During wildfires, precast concrete walls help provide protection to human life and the occupant's possessions. As an exterior wall, concrete that endures a fire can often be reused when the building is retrofitted.

The fire endurance of concrete can be determined by its thickness and type of aggregate. The American Society for Testing & Materials (ASTM) E119 lists procedures for determining fire endurance of building materials. Another good resource is PCI's *MNL 124-89: Manual on Design for Fire Resistance of Precast, Prestressed Concrete*.

Fire endurance is defined as the period of resistance to a standard fire exposure as defined by ASTM E119 that lapses before an "end point" is reached. Three end points are critical:

1. **Structural end point.** Loadbearing components must sustain the applied loading for the duration of the required fire endurance. Collapse prior to that is an obvious end point.
2. **Heat-transmission end point.** When the temperature increase of the unexposed surface of floors, roofs, or walls reaches an average temperature of 250 °F or a maximum of 325 °F at any one point.
3. **Flame-passage end point.** Holes, cracks, or fissures allowing flames or gases hot enough to ignite cotton waste to pass through must not form.

Structural End Points

Concrete generally fails by heat transmission long before structural failure, whereas other construction materials fail by heat transmission when collapse is imminent.

Heat-Transmission End Points

For single-course precast concrete slabs or wall panels, a two-hour fire endurance means that thermocouples, measuring the passage of heat through the thickness of the wall, are recording an average temperature rise of 250 °F or a maximum temperature reading of 325 °F (see Reference 1).

Slabs or wall panels faced with protective materials can provide added endurance. The accompanying table shows the fire endurance of concrete slabs with $^5/_8$-in. gypsum wallboard (Type X) for two cases:

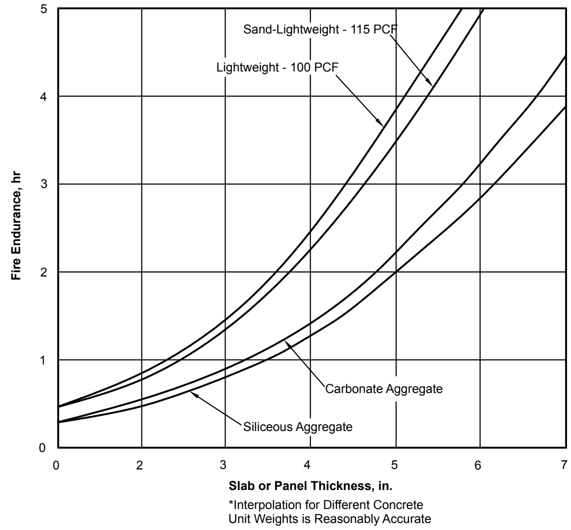
1. A 6-in. air space between the wallboard and slab.
2. No space between the wallboard and slab.

The specified materials and techniques for attaching wallboard should be similar to those used in the test on which the data are based (see Reference 2).

Thickness (in.) of Concrete Panel for Fire Endurance of				
	With no air space		With 6 in. air space	
Aggregate	2 hr	3 hr	2 hr	3 hr
Sand-lightweight	2.5	3.6	2.0	2.5
Carbonate	2.8	4.0	2.0	2.7
Siliceous	2.9	4.2	2.0	2.8

Thickness of concrete slabs or wall panels faced with 5/8 in. Type X gypsum wallboard to provide fire endurances of 2 and 3 hours.

Heat transmission through a ribbed or corrugated panel is influenced by the thinnest portion of the panel and by the panel's "equivalent thickness." This term is defined as the net cross-sectional area of the panel divided by the width of the cross section. In calculating the net cross-sectional area of the panel, portions of ribs that project beyond twice the minimum thickness should be ignored (see Reference 3).



Fire endurance (heat transmission) of concrete slabs or panels

Multi-course assemblies, such as floors and roofs, often consist of concrete base slabs with overlays or undercoatings of other types of concrete or insulating materials. In addition, roofs generally have built-up roofing. If the fire endurance of the individual courses is known, the fire endurance of the composite assembly can be estimated (see Reference 4).

Precast concrete insulated sandwich wall panels must conform to IBC requirements. Those regulations state that where noncombustible construction is specified, combustible elements in walls are limited to thermal and sound insulation having a flame-spread index of 25 or less.

When the insulation is sandwiched between two layers of noncombustible material such as concrete, the maximum flame-spread index allowed is 100, except that it shall not exceed 75 for foam-plastic insulation. When insulation is not installed in this manner, it is required to have a flame spread of not more than 25. Data on flame-spread classifications are available from insulation manufacturers.

Cellular plastics melt and are consumed at about 400 to 600 °F. Thus, additional thickness or changes in composition probably have only a minor effect on the fire endurance of sandwich panels. The danger of toxic fumes caused by burning cellular plastic is practically eliminated when the material is completely encased within concrete sandwich panels. Until more definitive data are provided, PCI recommends that 5 minutes be considered as the value for R for any layer of cellular plastic 1 in. or greater (see Reference 5), where R is the fire endurance rating of an assembly.

Flame-Passage End Points

Joints between panels should be detailed so that passage of flame or hot gases is prevented, and transmission of heat does not exceed the limits specified in ASTM E119. Concrete wall panels expand when heated, so the joints tend to close during fire exposure.

Noncombustible materials that are flexible, such as ceramic-fiber blankets, provide thermal, flame, and smoke barriers. When used with caulking, they can provide the necessary weather tightness while permitting normal volume-change movements. Joints that do not move can be filled with mortar.

Where no openings are permitted, the fire endurance required for the wall should be provided at the joints. Joints between adjacent precast floor or roof elements may be ignored in calculating the slab thickness provided that a concrete topping at least 1 1/2 in. thick is used.

Where no concrete topping is used, joints should be grouted to a depth of at least one-third the slab thickness at the joint, or the joints should be made fire-resistive in a manner acceptable to the authority having jurisdiction. No joint treatment is required for parking structures constructed with pretopped double tees (see Reference 6).

Codes and Economics

An important aspect of dealing with fire endurance is to understand what the benefits are to the owner of a building in the proper selection of materials incorporated in the structure. These benefits fall into two areas: codes and economics. While code requirements must be met, designers typically have many options in the specification of materials and assemblies that meet these regulations.

Economic benefits associated with increased fire endurance should be considered at the time decisions are made on the structural system. Proper consideration of fire-resistive construction through a life-cycle cost analysis will show the owner the amount of economic benefits that will accrue through the use of different types of construction. These benefits can include lower insurance rates, larger allowable gross area, fewer stairwells and exits, increased value for loan purposes, longer mortgage terms, and better resale value (see Reference 7).

Several key areas of code compliance allow owners and designers to provide effective fire protection at an economical cost. The three key areas are:

1. **Minimum standards.** A fire rating is not the same as fire safety. The IBC includes a variety of compromises. Code trends generally emphasize sprinkler installations by providing trade-offs that encourage their use. These active systems offer valuable protection, but they also include trade-offs such as more liberal fire-separation areas and other changes that decrease required wall and floor performance.

2. **Building materials.** Wood and steel generally perform poorly in fires. Both must be treated, coated, or covered to meet fire requirements, which increases construction costs. Wood is a natural fuel source and steel begins to fail at 1200 °F. Concrete begins to melt at 2200 °F.

3. **Sprinklers.** Automatic sprinklers are a desirable, active fire-suppression system and can help control fire spread. But they should not replace passive fire-suppression systems that are designed to inherently protect a building without any mechanical activation required. Relying on active-suppression systems alone can produce an inadequate response during a fire emergency.

A design approach that stresses compartmentalization offers a more fundamental method to protect lives and property. Compartmentalization uses passive, noncombustible floors and walls, such as those made of precast concrete, to construct sections of the building as separate modules that confine fire to a specific area. Once constructed into the building, these passive protectors will protect the building throughout its life.

Noncombustible compartmentalization, combined with an inherently fire-resistant/tolerant structural frame, provide the best combination of economics and protection that owners and users seek. When this passive design combines with other safety measures, including sprinklers and early-warning detection systems, a balanced design approach is achieved (see Reference 8).

A variety of precast concrete components can be used in creating a complete passive-design system for a building. Foremost among these are:

- **Hollow-core slabs**, which serve as combined floor/ceiling systems and can also be used as wall panels in either vertical or horizontal configurations.
- **Wall panels**, which offer high fire ratings and work with other components to create a noncombustible envelope. Insulated sandwich wall panels can also be used.
- **Double tees**, which can be used similar to hollow-core planks for roofs, ceilings, floors, or wall panels.
- **Columns and beams**, which create a framework that will resist intense heat and will not add fuel to a fire.

A total-precast concrete system provides an effective design for minimizing fire damage and containing the effects within the smallest space possible for the longest time.

The information above will provide for a structure with acceptable criteria for fire resistance. The designer and owner should also consider the following factors when designing for fire:

- Contain high heat, which can melt or ignite combustible materials.
- Contain smoke that can blind, choke, and ruin building contents. Smoke is often generated by a sprinkler suppression process which may be unavoidable.
- Contain toxic gases that are given off by plastics, synthetics and chemicals when they burn.
- Confine the fire event to its place of origin by using precast concrete components to create compartments.
- Reduce the fuel content of the building by using noncombustible material whenever possible.
- Create several noncombustible compartments in the building
- Understand that the local minimum code requirements may not be adequate to achieve the fire protection that your building and its occupants should have.

A 2005 study sponsored by the Fire Safe Construction Advisory Council compared construction costs among five building systems and found that a compartmentalized construction approach using concrete-based methods costs generally less than 5% of the overall construction cost. The group noted that this amount was less than the contingency budget typically recommended for the owner to carry for unanticipated expenditures during the project.

The project evaluated the impact of building a fire-resistant, multifamily, residential structure using five separate building techniques, to meet requirements of the 2003 IBC. The five systems comprised:

- Conventional wood framing with a wood-floor system using Type 5A or 5B construction;
- Light-gage steel framing with a cast-in-place concrete floor system on a metal form deck;
- Loadbearing concrete masonry construction with a precast concrete plank floor system or a cast-in-place concrete floor system;
- Precast concrete walls with a precast concrete floor system; and
- Insulated concrete form (ICF) walls or interior bearing walls made with concrete masonry units (CMU) with a precast concrete plank floor system or a cast-in-place concrete floor system.

In each case, except the conventional wood-frame system, it was assumed that the partition walls within the building would be constructed using metal studs finished with gypsum board.

The studied building was a four-story structure encompassing 25,000 ft^2 of space per floor. Two models were created, one with single-bedroom layouts and another with a mix of one- and two-bedroom layouts to address the variety of construction configurations commonly found in the multifamily dwelling marketplace. The team chose three specific locations in which to locate their projects (Framingham, Mass.; Harrisburg, Pa.; and Towson, Md.) to provide diversity in labor and material costs.

The study's consensus was that the costs associated with using a compartmentalized construction method that took advantage of precast concrete's benefits required less than 2% more of the total construction cost.

In addition, although precast concrete's initial in-ground cost was higher, the design did not fully play to the advantages that a total-precast concrete design would offer, as the designers created a layout that could be standardized for use by all material options. Those general parameters would not be necessary if a design intended to use precast concrete from the beginning, and the difference in costs would be lower.

The costing parameters were also unable to take into consideration the schedule advantages that precast concrete's fast erection would provide. Additional advantages, including longer span capability to reduce columns, can provide sufficient cost effectiveness to eliminate the cost differential.

The use of concrete materials can also provide long-term benefits, the report noted. Materials like concrete masonry, precast concrete, and cast-in-place concrete offer advantages beyond their inherent fire performance, such as resistance to mold growth and damage from vandalism, as well as minimal damage caused by water and fire in the event of a fire. Those attributes can require reduced cleanup costs and quicker reoccupation of the structure (see Reference 9).

References:

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2. Chapter 9.3.6.1, "Fire Resistance: Single Course Slabs or Wall Panels," MNL-120-04: *PCI Design Handbook, Sixth Edition.*
3. Chapter 9.3.6.3, "Fire Resistance: Ribbed Panels," MNL-120-04: *PCI Design Handbook, Sixth Edition.*
4. Chapter 9.3.6.4, "Fire Resistance: Multi-Course Assemblies," MNL-120-04: *PCI Design Handbook, Sixth Edition.*
5. Chapter 9.3.6.5, "Fire Resistance: Sandwich Panels," MNL-120-04: *PCI Design Handbook, Sixth Edition.*
6. Chapter 9.3.6.6, "Fire Resistance: Treatment of Joints between Wall Panels," MNL-120-04: *PCI Design Handbook, Sixth Edition.*
7. Chapter 9.3.10, "Fire Resistance: Code and Economic Considerations," MNL-120-04: *PCI Design Handbook, Sixth Edition.*
8. MK-33-03: *Precast Concrete Fire Prevention: Setting the Record Straight.*
9. Executive Summary Report, "Fire Safe Construction Cost Study," November 2, 2005, Commission Number 05119.

Resources:

Executive Summary Report, "Fire Safe Construction Cost Study," November 2, 2005, Commission Number 05119.

MK-33-03: *Precast Concrete Fire Prevention: Setting the Record Straight.*

MNL-120-04: *PCI Design Handbook, Sixth Edition.*

MNL-122-07: *PCI Architectural Precast Concrete Manual, Third Edition.*

MNL-124-05: *Design for Fire Resistance of Precast Prestressed Concrete, Third Edition.*

MNL-126-98: *Manual for the Design of Hollow-Core Slabs, Second Edition.*

PCI Journal:

"Are We Protected From Fire in Buildings?" *PCI Journal*, January-February 2005, pp. 118-123.

EARTHQUAKE RESISTANCE

Precast concrete can be designed to resist seismic events, and recent advancements in connection approaches provide additional design options.

Earthquakes in Guam, the United States (Richter scale 8.1); Manila, the Philippines (Richter scale 7.2); and Kobe, Japan (Richter scale 6.9), have subjected precast concrete buildings, using both architectural cladding and structural components, to some of nature's deadliest forces. During the 1994 Northridge, Calif., earthquake (Richter scale 6.8), in which damage was estimated at $20 billion, most engineered structures within the affected region performed well, including structures with precast concrete components.

In particular, significant damage was not observed in precast concrete cladding due to either inadequacies of those components or inadequacies of their connections to the building's structural systems, nor was damage observed in the precast concrete components used for the first floor or first-floor support of residential housing. Parking structures with large plan areas, regardless of structural system, did not perform as well as other types of buildings (see Reference 1).

The key reason designers have gravitated toward precast concrete components is because they can span long distances between attachments to the main structure. Design methods and details have been developed to accommodate these applications in seismic areas.

Earthquakes generate horizontal and vertical ground movement. When the seismic waves pass beneath a structure, the foundation tends to move with the ground, while the superstructure remains in position. The lag between foundation and superstructure movement causes distortions and develops forces in the structure. As the ground moves, distortions and forces are produced throughout the height of the structure, varying with the ground acceleration and the resonance of the building.

Ductility Needs

The current philosophy for the design of earthquake-resistant structures permits minor damage for moderate earthquakes and major damage for severe earthquakes, provided complete collapse is prevented. The design details often require large, inelastic deformations to occur to dissipate energy and shed inertial forces. This is achieved by providing member and connection ductility.

While this ductility helps resist total collapse, the resulting distortions may lead to significant damage to mechanical, electrical, and architectural elements. Seismic damage can be minimized by setting limitations on structural deflections, usually considered as interstory drift.

The response of a structure to the ground motion of an earthquake depends on the structural system's dampening characteristics and on the distribution of its mass. With mathematical idealization, a designer can determine the probable response of the structure to an imposed earthquake.

New Code Requirements

A number of changes have been made to existing codes in recent years based on new research and observations. These include:

- Recognition of jointed-panel construction as an alternative to emulation of monolithic construction.
- Achieving ductile structural behavior by using “strong” connections that remain elastic while nonlinear action (plastic hinging) occurs in the member away from the connection.
- Modification of drift computation and limiting drift.
- Deformation compatibility of structural elements and attached nonstructural elements.
- Additional soil-type classifications.
- Special considerations for building sites located near seismic faults.
- Special considerations for structures possessing redundancy.

(See Reference 2.)

The Paramount’s use of a precast hybrid, moment-resisting frame as part of its structural system is that it creates a restoring force provided by its elastic, post-tensioned strands that rights the building following a seismic event. Architect of Record: Kwan Henmi, Architecture/Planning; Photo: David Wakely Photography.

PCI has worked in several of these areas to help create new design solutions that provide more effective responses to seismic events. A 10-year study by the Precast Seismic Structural Systems (PRESSS) Research Program produced three new approaches that have been or are in the process of being codified. These three systems are:

1. **A hybrid post-tensioned precast frame**, which was codified in 1999. Developed by the National Institute of Standards & Technology (NIST), this method has the precast concrete beams connected to multistory columns by unbonded, post-tensioned strands that run through a duct in the center of the beam and through the columns. Mild steel reinforcement is placed in ducts at the top and bottom of the beam, which is sleeved through the column and grouted.

   The reinforcement yields alternately in tension and compression and provides energy dissipation, while the post-tensioning strands essentially act as “rubber bands” that help right the structure after the seismic event ends. There are no column corbels, with the vertical shear resistance provided by the post-tensioning strand. The post-tensioning steel balances the mild steel reinforcement so the frame re-centers after flexing during a seismic event (see Reference 3).

2. **A pretensioned precast frame**, which is applied at locations where the most economical connection method features one-story columns with multispan beams. The multispan beams are cast with partially debonded pretensioning strand set on the columns. The column’s reinforcing steel extends through the sleeves inside the beams. Reinforcing-bar splices ensure continuity above the

A moment-frame beam form illustrates the center PVC duct that holds the prestressing tendons and the six corrugated tubes for the mild steel bars used in the hybrid system.

Rigorous tests performed on an experimental structure proved the success of the PRESSS program's connection technology.

beam. As the frame displaces laterally, the debonded strand remains elastic. While the system dissipates relatively less energy than other systems, it re-centers the structure after a major seismic event (see Reference 4).

Although this frame has performed satisfactorily in tests, it would not be allowed to act as the sole seismic-force-resisting system in regions of high seismic risk or for structures assigned to high seismic-performance or design categories under Section 21.6.3 of ACI 318.

Such frames can be designed to satisfy all requirements for use as intermediate moment frames. These frames should also be acceptable for intermediate moment frames when designed using the same factors as those specified in the governing building code for cast-in-place concrete construction.

Analyses are still being done to verify the applicability of this system to various high seismic events. In the interim, the satisfactory performance of the frames in the PRESSS tests can be used to seek building-department approval for these designs in moderate seismic-risk zones and for structures assigned to intermediate seismic performance or design categories (see Reference 5).

3. **A shear-wall system.** The PRESSS shear-wall design used an innovative approach for anchoring and connecting jointed walls to lengthen the structural period and reduce the design-based shear forces. Gravity loads were mobilized to partially resist overturning from the lateral ground motions. The system also considered the behavior of the jointed shear-wall system when the wall lifts off and rocks, along with its effect on design forces. An important level of hysteretic damping was added to the wall system through the connection devices located at the vertical joint between the wall panels.

   U-shaped flexure plates were used for vertical joint-connection devices where damping was achieved with flexural yielding of the plates. Unbonded post-tensioning forces re-centered the wall system when the load was removed, so there would be minimal residual drift after a design-level earthquake. Re-centering was ensured by relating the elastic capacity of the post-tensioning system to the yield strength of the panel-to-panel connection.

   The shear wall is expected to displace laterally to approximately 2% of story drift under a design-level earthquake. This is consistent with the drift limits specified by existing standards. Should the designer desire smaller design-story drift or less energy dissipation, the balance of post-tensioning and energy-dissipating connections could be altered (see Reference 6).

   This shear-wall design and test has led to the adoption of an allowance for nonemulative design of special precast concrete shear walls to be accepted for the 2003 edition of the National Earthquake Hazard Reduction Program (NEHRP) Provisions (see Reference 7).

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7. "Codification of Precast Seismic Structural Systems: An Update," *PCI Journal*, May-June 2006, pp. 46-49.

Contract Document Requirements

Many precast concrete buildings are designed by a team including the engineer of record, the precast manufacturer's engineer, and possibly a specialty engineer retained by the manufacturer. It is the engineer of record's responsibility to provide pertinent information on the contract documents so that others providing the seismic design of the structure use the correct information for the location of the project. The 2006 International Building Code indicates what these requirements are in Section 1603.

Resources:

IBC-1-01: Impact of the Seismic Design Provisions of the International Building Code.

MNL-120-04: *PCI Design Handbook, Sixth Edition.*

MNL-122-07: *PCI Architectural Precast Concrete Manual, Third Edition.*

MNL-123-88: *Design and Typical Details of Connections for Precast and Prestressed Concrete, Second Edition.*

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"Apartment Skyscraper Shows Precast's Seismic Capabilities," *Ascent*, Summer 2000, pp. 40-43.

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"Seismic Design of Lightly Reinforced Precast Concrete Rectangular Wall Panels," *PCI Journal*, July-August 2002, pp. 104-121.

"Seismic Design of Partially Post-Tensioned Precast Concrete Walls," *PCI Journal*; July-August 2005, pp. 100-125.

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"Seismic Design Methodology for Precast Concrete Diaphragms Part 2: Research Program," *PCI Journal*, November-December 2005, pp. 14-31.

"Seismic Design Provisions in U.S. Codes and Standards: A Look Back and Ahead," *PCI Journal*, January-February 2002, pp. 94-99.

"Seismic Design Recommendations for Precast Concrete Diaphragms in Long Floor Span Construction," *PCI Journal*, November-December 2003, pp. 46-64.

"Seismic Tests of Beam-to-Column Connections in a Precast Concrete Frame," *PCI Journal*, May-June 2002, pp. 70-89.

"Structural and Economic Benefits of Precast/Prestressed Concrete Construction," *PCI Journal*, July-August 2001, pp. 34-43.

"Trends in the Seismic Design Provisions of U.S. Building Codes," *PCI Journal*, September-October 2001, pp. 98-103.

"Untopped Precast Concrete Diaphragms in High-Seismic Applications," *PCI Journal*; November-December 2002, pp. 94-99.

WIND RESISTANCE (TORNADOS AND HURRICANES)

In most areas of the United States using IBC 2003, the earthquake loading will be more critical than wind. But wind loads should be checked, and more emphasis today is being put on designing structures to withstand tornado and hurricane impacts, certainly in coastal areas where they are being addressed through supplemental codes and other local requirements.

Precast concrete structural systems and architectural panels provide significant benefits in meeting wind-resistance needs. A calculation for determining proper windloads for precast concrete structures can be found in MNL-120-04: *PCI Design Handbook, Sixth Edition* (see Reference 1).

Tornados

Single-family homes provide the greatest danger of destruction during a tornado. In regions of the country where tornados can wreak havoc on single-family homes, precast concrete designs can provide a durable, wind-resistant structure. Several key elements are desired in designing a home to resist tornado damage. These include:

Eight-four unit assisted-living facility built to withstand an F-4 tornado. Photo: Dukane Precast Inc.

- Connections that securely tie the house together from roof to foundation, providing protection for winds up to 130 mph.
- Impact-resistant roof materials that better withstand high winds and fire.
- Windows and doors with higher wind- and water-design pressure ratings and a garage door capable of withstanding impact from large objects.
- Construction materials and siting work that eliminate the threat of flood or wildfire.

A number of designers and precasters have worked together to create precast concrete housing designs across the country. These designs not only protect homes from wind damage but also cut energy costs, are constructed quickly and provide a range of aesthetic designs that can blend with any neighborhood (see Reference 2).

A variety of precast concrete components are used to create tornado-resistant housing. These include foundation walls, loadbearing precast concrete wall panels with an architectural finish, and hollow-core plank for floors and roofing. Precast concrete's inorganic and noncombustible composition ensure the housing will not generate mold or mildew following torrential rains, nor will they catch on fire should sparks ignite flammables.

Hollow-core plank is a key component in housing. Typically, one thickness is used as the lower level's ceiling and the upper level's floor. It is also used as the roofing substructure, again serving as the ceiling of the lower level at the same time. The long spans available with hollow-core planks are particularly useful for opening up interiors while providing a safe room for protection from high winds.

Precast concrete panels offer several different uses in housing designed to withstand tornados, including façades and foundation walls. Insulated panels, typically 10 by 16 ft in size, are used as foundation walls, with an insulating board on their back (interior) side. The walls offer more than twice the strength of concrete-block walls (5000 psi compared to 2000-2400 psi) and minimize seams through which moisture can penetrate.

Precast concrete homes provide significantly more protection from wind-borne debris than other building materials, according to tests conducted by the Portland Cement Association. The group tested various walls with the impact of a 2x4 wood stud traveling at 100 mph, the equivalent of wind-borne debris during a tornado with 250-mph winds. About 90% of tornados have wind speeds of less 150 mph, the group says. Of all materials tested, only the concrete design stopped the debris from penetrating the wall. All others suffered penetration (see Reference 2).

The actual cannon used. Spectators even got to touch the 2 x 4 to confirm the authenticity. In the distance are the panels ready to be tested with the safety wall behind. Photos: Susan Leader.

In test one, the 2 x 4 went through this vinyl sided, wood-frame wall panel like a hot knife through butter. Notice the entry, and the exit holes. Not only are they clean holes, but it didn't even slow the projectile down.

Note as well the significant hole in the safety wall behind the panel in the photo to the right.

Test two shot the 2 x 4 through a brick wall with wood frame. Surprisingly, it's not all that much safer then siding. What you don't see are the pieces of brick that went flying through the back side of the panel. This wall introduced even more projectiles into the house.

Test three smashed a 2 x 4 through a brick home with steel framing. This damage is still rather significant, but in this test the projectile did not travel through the wall. Looking at the back side shows it would take only slightly more force to push all the way through.

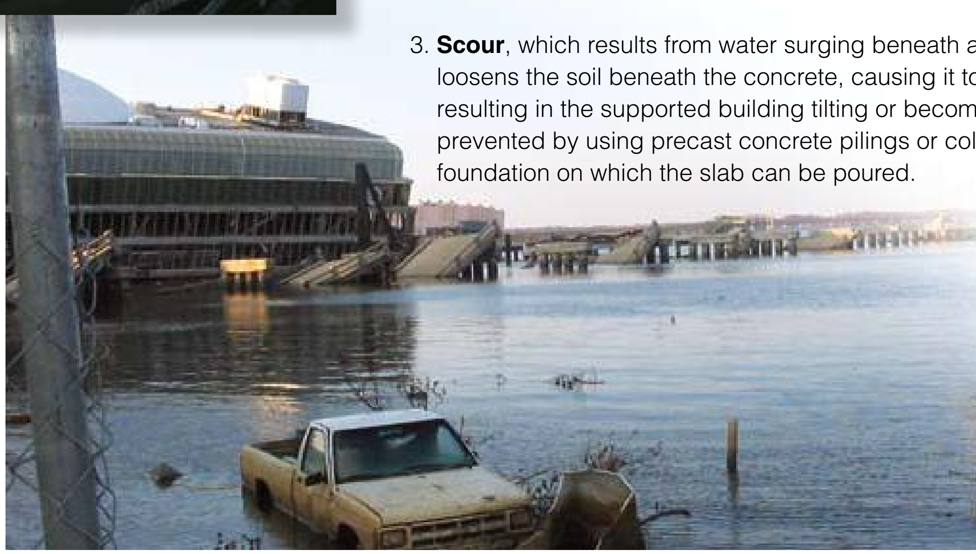
Now for the real test: hurl a 2 x 4 at a precast wall panel at 112 mph. The result: no damage visible, not even a chip.

Wall Type:	Test Wall Description:	Speed of Debris:	Results:
Wood frame:	$\frac{5}{8}$-in. gypsum board interior finish, 2x4 wood studs at 16 in. o.c., $3\frac{1}{2}$-in. batt insulation, $\frac{3}{4}$-in. plywood sheathing, vinyl-sided exterior finish	109 mph	The debris missile perforated completely through the wall assembly. Little damage to missile.
	$\frac{5}{8}$-in. gypsum board interior finish, 2x4 wood studs at 16 inches o.c., $3\frac{1}{2}$-in. batt insulation, $\frac{3}{4}$-in. plywood sheathing, 4-in. brick veneer with 1-in. air space	69.4 mph	The debris missile perforated completely through the brick veneer and the interior finish. Minor damage to missile.
Steel frame:	$\frac{5}{8}$-in. gypsum board interior finish, steel studs at 16 in. o.c., $3\frac{1}{2}$ in. batt insulation, $\frac{3}{4}$-in. plywood sheathing, vinyl-sided exterior finish	103.5 mph	The debris missile perforated completely through the wall assembly. Little damage to missile.
	$\frac{5}{8}$-in. gypsum board interior finish, 2x4 wood studs at 16 in. o.c., $3\frac{1}{2}$-in. batt insulation, $\frac{5}{8}$-in. gypsum board sheathing, synthetic stucco exterior finish	50.9 mph	The debris missile perforated completely through the wall assembly. No damage to missile.
Concrete:	6-in.-thick reinforced concrete wall, #4 vertical reinforcing bars, 12 in. o.c, no finishes	109 mph	No cracking, front-face scabbing, or back-face spalling of concrete seen.
	6-in.-thick reinforced concrete wall, #4 vertical reinforcing bars, 24 in. o.c, no finishes	102.4 mph	No cracking, front-face scabbing, or back-face spalling of concrete seen.
ICF:	Block ICF foam forms, 6-in.-thick flat concrete wall, #4 vertical reinforcing bars, 12 in. o.c., vinyl siding (tested twice with similar results)	103.8 mph	Debris penetrated vinyl siding and foam form. No cracking, front-face scabbing, or back-face spalling of concrete wall seen.
	Block ICF foam forms, 6-in.-thick flat concrete wall, #4 vertical reinforcing bars, 24 in. o.c., 3-in. brick veneer with ties spaced 1 in. each way	99 mph	Debris penetrated and cracked brick veneer. Foam form dented. No cracking, front-face scabbing, or back-face spalling of concrete wall seen.
	Panel ICF foam forms, 4-in.-thick flat concrete wall, #4 vertical reinforcing bars, 24 in. o.c., vinyl siding	96.7 mph	Debris penetrated vinyl siding and foam form. No cracking, front-face scabbing, or back-face spalling of concrete wall seen.
	Block ICF foam forms, variable thickness "waffle" concrete wall, 6 in. maximum thickness, and 2 in. minimum thickness, #4 vertical reinforcing bars in each 6-in. vertical core at 24 in. o.c, synthetic stucco finish (tested twice with similar results)	100.2 mph	Debris penetrated synthetic stucco finish and foam form. Impact of wall at 2-in.- thick section. No cracking, front-face scabbing, or back-face spalling of concrete wall seen.

Note: All concrete tested had 3000-psi compressive strength with a maximum aggregate size of 3/4 in. with a 6-in. slump.
Source: Portland Cement Association

Photo: ©PhotoDisc.

Much of the damage done to precast concrete parking structures along the Gulf Coast by Hurricane Katrina was caused by the high storm surge, which flooded the structures and caused double tees to be puched off their supports. Otherwise, the material performed well. (Three photos below).



Hurricanes

The devastating impact of recent hurricanes, notably Katrina and Rita, have put a spotlight on designing to withstand the highest levels of these forces, which are more complex than those associated with tornados. Hurricanes produce not only high winds but also forces associated with the impact from high waves and immense amounts of water overwhelming a structure.

Precast concrete components can help to withstand these forces if designers take into account all of the actions involved and how the components must react to them. The factors that designers must consider include:

1. **High winds**, which can be dealt with similarly to those in tornados and do not pose a substantial risk for buildings built of precast concrete. Examination of projects exposed to the high winds of Hurricane Katrina indicated that wind loads for precast concrete buildings were well accounted for. Wind-borne debris creates the largest problem and results in only chipping or cracking in some instances at the high end of the wind speeds.

   To be certain of withstanding wind loads in these high-risk areas, designers should overcompensate for potential problems. Designing for a 200-mph wind and using reinforcement to meet that level of force should protect the structure under any situation. Modifying designs to reduce surface area will also help to ensure that wind loads do not create a problem.

2. **Surge**, in which large amounts of water rush over the land and up to buildings. Often, this water carries with it loose debris that can be substantial in nature and can act as a battering ram against a building. In some cases, if the surge is high enough, the debris can impact the building at a height that was not designed to withstand such force. This can cause damage to the stems on double tees, particularly on parking structures. Creating a precast concrete soffit or other protective shield that prevents large debris from surging through the structure at such a height can mitigate this concern.

3. **Scour**, which results from water surging beneath a slab on grade. This action loosens the soil beneath the concrete, causing it to deteriorate or break up, resulting in the supported building tilting or becoming unstable. This can be prevented by using precast concrete pilings or columns to create a stable soil foundation on which the slab can be poured.

4. **Buoyancy**, in which the water levels rise above the first floor of a structure, such as a parking structure, where the levels are supported by double tees. Designs typically do not account for tees being lifted from their position. Connections must account for this possibility in the areas of the highest concern.

5. **Structure orientation**, which should provide the smallest exposure to the likely direction of a hurricane in areas most likely to be hit. Interiors also should take the concept of surging water into account. For instance, in parking structures, ramps should be faced away from the ocean to allow water to flow through the structure rather than be blocked by it. Creating fewer obstacles for the likely path that water will follow during a hurricane will minimize damage.

Salt-water damage, in the form of corrosion or deterioration of the components after water recedes, should not create a long-term problem. In many instances, precast concrete components produced for these marine environments already include additives that hinder the potential for corrosion.

Home Designs

Designing homes for wind loads can follow the same concepts as expressed for tornado designs, and these concepts are available throughout the country from precasters. Meeting the needs for protecting against surging water requires additional consideration.

With surges in New Orleans, La., of 12 ft or more, one design option is to use precast concrete piles or columns to create a first-level garage on top of which the living space can be created, using precast concrete panels to create the shell.

The home still can have wood and drywall interior framing, although if the surge or other water damage reaches the interior, all these materials may have to be completely removed to remediate mold. Even then, the shell and structural integrity remain intact, eliminating the need to start from scratch (see Reference 2).

Concrete is not damaged by water. In fact, concrete that does not dry out continues to gain strength in the presence of moisture. Concrete submerged in water absorbs small amounts of water over long periods of time, and the water does not damage the concrete. In flood-damaged areas, concrete buildings are often salvageable.

Concrete will only contribute to moisture problems in buildings if it is enclosed in a system that does not let it breathe or dry out, and moisture is trapped between the concrete and other building materials. For instance, vinyl wallcoverings in hot and humid climates will act as a vapor retarder, allowing moisture to become trapped between the concrete and wall covering. For this reason, impermeable wallcoverings (vinyl wallpaper) should not be used (see Reference 3).

References:

1. Chapter 3.2.2, "Wind Loads," MNL-120-04: *PCI Design Handbook, Sixth Edition.*
2. "Designing for Hurricane Zones," *Ascent*, Summer 2006, pp. 20-25.
3. "Achieving Sustainability with Precast Concrete," *PCI Journal*, January-February 2006, pp.42-61.

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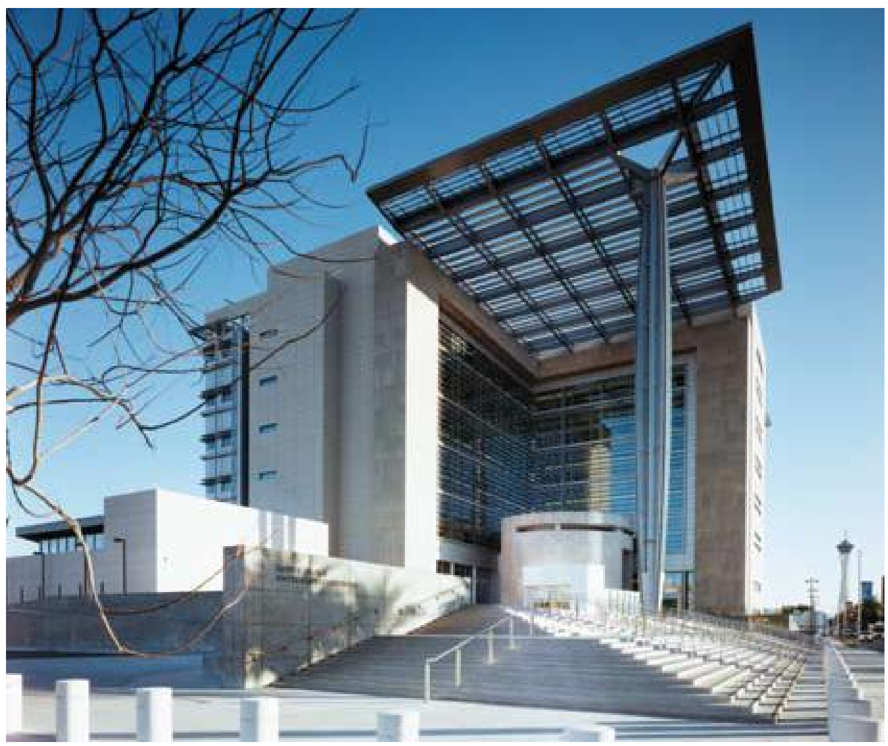
EXTERNAL BLAST RESISTANCE

In today's environment of enhanced risk, some facilities require protective design and the management of risk. There are many design options available to reduce the risk to any building. Economically feasible design for antiterrorism/force protection (AT/FP) requires an integrated approach encompassing many aspects of the development, including siting, operation programming of interior spaces, and the use of active and passive security measures using provisions of both technology and human involvement.

The objective of blast-resistant design is to provide an acceptable level of safety to building occupants in the event of an explosion. Considerable damage is usually acceptable as long as components remain attached to the building and the building does not experience a progressive collapse.

Planning must include all involved members of the design team (owners, architects, structural engineers, and blast consultants). They must agree upon the blast forces to be withstood as well as the risk and vulnerability assessment to the occupants and the protection levels that can be achieved within budget.



Lloyd D. George Federal Courthouse, Las Vegas, Nev.; Architect: Langdon Wilson; Photo: Langdon Wilson.

The first major federal courthouse built after the 1995 blast in Oklahoma City contains features intended to avoid a catastrophic collapse in the event of a terrorist attack. The precast concrete panels were designed to be more ductile than conventional panels so they could absorb as much of a bomb blast as possible without destroying the connections that tie them to the main structure. Note: Bollards used to increase the standoff distance.

Probability Considerations

An awareness of a blast threat from the beginning of design helps to make decisions early about what the priorities should be for the facility. Including protective measures as part of the discussion regarding trade-offs early in the process helps to clarify the issues.

The willingness to pay the additional cost for protection against blast hazards is a function of the "probability of regrets" in the event that a sizable incident occurs. In some situations, with some buildings, the small probability of an incident may not be compelling enough to institute the design enhancements.

This logic will likely lead to a selection process in which buildings stratify into two groups: those that incorporate no measures at all or only minimal provisions and those that incorporate high levels of protection. It also leads to the conclusion that it may not be appropriate to consider any but the most minimal measures for most buildings.

Key Considerations

Unlike seismic and wind loads, blast loads have an extremely short duration (i.e., milliseconds). Often, the large mass associated with the overall building response provides enough inertia so the building's framing does not need to be strengthened to resist blast loads. The lateral force-resisting system on smaller one- and two-story buildings generally needs to be designed to resist blast loads. Conventional foundation systems are almost always adequate to resist the short-duration reaction loads from building response to blast loads.

Quantifying blast events into overpressures and time durations is a science of its own. Blast engineers should be consulted when explosion scenarios are to be considered in the building's design.

A key consideration will be designing the building's façade, which is the structure's first defense against an exterior explosion. How the façade responds to this loading will significantly affect the structure's behavior. The need for comprehensive protection of occupants within the structure will likely cause window sizes to decrease in height and width and increase in thickness. Attachments likewise will become more substantial.

Architectural precast concrete can be designed to mitigate the effects of an explosion and thereby satisfy requirements of the General Services Administration (GSA) and the Department of Defense (DOD). Protecting the entire façade, however, will impose a great cost regardless of the material used. To provide the best protection for occupants, designers should plan for the building and its cladding to remain standing or attached long enough to protect occupants from injury or death resulting from flying debris and to evacuate everyone safely (see Reference 1).

The shape of the building can affect the overall damage. A U- or an L-shaped building can trap the shock wave, which may increase blast pressure locally because of the complex reflections created. Large or gradual re-entrant corners have less effect than small or sharp re-entrant corners. In general, convex rather than concave shapes are preferred. The reflected pressure on the surface of a circular building is less intense than on a flat building (see Reference 2).

Currently, no specific standards or guidelines exist for blast design from either the American Concrete Institute (ACI) or the PCI.

All building components requiring blast resistance should meet the criteria required for GSA or DOD facilities. They should be designed using established methods and approaches for determining dynamic loads and dynamic structural response. Design and analysis approaches should be consistent with the following manuals:

- U.S. Departments of the Army, Navy and Air Force, "Structures to Resist the Effects of Accidental Explosions," Revision 1 (Department of the Army Technical Manual TM 5-1300, Department of the Navy Publication NAVFAC P-397, Department of the Air Force Manual AFM 88-22).
- DAHSCWEMAN, "Technical Manual – Design and Analysis of Hardened Structures to Conventional Weapon Effects; PSADS (Protective Structures Automated Design System), Version 1.0." (It incorporates Army TM 5-855-1, Air Force AF JMAN32-1055, Navy NAVFAC P-1080, and Defense Special Weapons Agency DAHSCWEMAN-97).
- Unified Facilities Criteria, "Design and Analysis of Hardened Structures to Conventional Weapons Effects," U.S. Department of Defense, UFC 3-340-01, June 2002.
- Hyde, D. "ConWep – Application of TM5-855-1," U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., August 1992.
- U.S. Department of the Army, Security Engineering, TM 5-853 and Air Force AFMAN 32-1071, Volumes 1-4, Washington, DC, Departments of the Army and Air Force, 1994.
- Air Force Engineering & Services Center, "Protective Construction Design Manual," ESL-TR-87-57, Prepared for Engineering & Services Laboratory, Tyndall Air Force Base, Fla., November 1989.
- U.S. Department of Energy, "A Manual for the Prediction of Blast & Fragment Loadings on Structures," Revision 1, DOE/TIC 11268, Washington, DC, Headquarters U.S. Department of Energy, July 1992.
- Unified Facilities Criteria, DOD Minimum Antiterrorism Standards for Buildings, UFC 4-010-01, U.S. Department of Defense, July 2002.
- Interim Antiterrorism/Force Protection Construction Standards – Guidance on Structural Requirements (Draft), U.S. Department of Defense, March 5, 2001.

Designing for blast resistance requires a comprehensive knowledge of explosive effects and fortification sciences, as described in DAHSCWEMAN (1998), in Technical Manual (TM) 5-855-1 (U.S. Department of the Army 1998), and in the Tri-Service Manual (TM-5-1300, U.S. Department of the Army, Navy, and Air Force 1990). The electronic version of the DAHSCWEMAN manual will greatly assist in applying blast-design concepts.

The report "Design for Physical Security—State of the Practice Report," prepared by the Structural Engineering Institute Task Committee, American Society of Civil Engineers (1999), addresses the design of structures to resist the effects of terrorist bombings and provides guidance for engineers (see Reference 3).

Creating Standoff Distance

Basic protection is produced by creating a minimum guaranteed distance between the blast source and the target structure. The setback zone restricts vehicular access by using dense components such as perimeter anti-ram bollards, large planters, low-level walls, or fountains. Creating this standoff distance helps minimize the design requirements for protecting the building cladding and structural elements.

The blast pressure is inversely proportional to the cube of the distance from the blast to the point in question. Current design standoff distances for blast protection vary from 33 ft to 148 ft, depending on the building's function.

Nimitz-MacArchur Pacific Command Center, Oahu, Hawaii; Architect: Wimberly Allison Tong & Goo Design; Photo: Gary Hofheimer Photography.

The four lowest stories of the building will be most impacted by a street-level blast and must follow accepted blast criteria. Those criteria are described in "Security Design Criteria for New Federal Office Buildings and Major Renovation Projects," issued May 28, 2001, by the Interagency Security Committee (ISC).

When designing with architectural precast concrete panels, designers should combine these criteria with the applicable blast-analysis standards. This combination ensures that the architectural precast concrete cladding system will be sufficiently sized, reinforced, detailed, and installed to resist the required blast-loading criteria.

The panels should also be tested in accordance with "Standard Test Method for Glazing and Window Systems Subject to Dynamic Overpressure Loadings (GSA-TS01-2003), released by the General Services Administration.

In addition to safely transferring the blast pressures into the supporting structure, the panels must be checked for their capacity to transfer the additional loading caused by the specified window framing and the blast-resistant glass units (see Reference 4).

Preventing Progressive Collapse

Several significant factors must be considered when designing buildings for blast resistance. These concepts include energy absorption, safety factors, limit states, load combinations, resistance functions, structural-performance, and structural redundancy to prevent progressive collapse of the building. This final one is most important, as a design satisfying all required strength and performance criteria would be unsatisfactory without redundancy.

To limit the extent of collapse of adjacent components requires five steps:

1. Highly redundant structural systems are designed.
2. The structure is analyzed to ensure it can withstand removal of one primary exterior vertical or horizontal load-carrying element, such as a column, beam, or portion of a loadbearing or shear-wall system without complete collapse of the entire structure.
3. Connections are detailed to provide continuity across joints equal to the full structural capacity of connected members.

4. Floors are designed to withstand load reversals due to explosive effects.

5. Exterior walls use one-way wall components spanning vertically to minimize blast loads on columns.

Strength and ductility (energy-dissipating capacity) are necessary to achieve high energy absorption. The structural materials and details must accommodate relatively large deflections and rotation to provide redundancy in the load path. Components with low ductility are undesirable for blast-resistant design.

Margins of safety against structural failure are achieved by using allowable deformation criteria. Structures subjected to blast loads are typically allowed to undergo permanent plastic deformation to absorb the explosion energy, whereas response to conventional loads is normally required to remain in the elastic range. The component's response is determined by how much deformation it is able to undergo before failure.

The more deformation the structure or member can provide, the more blast energy it can absorb. As long as the calculated deformations do not exceed the allowable values, a margin of safety against failure exists (see Reference 5).

Rigidity versus Ductility

A balance must be found between panel stiffness and the forces that the panel connections must resist. The proper balance must be evaluated by the structural engineer. Typically, the panels should have increased section thickness or ribs and have additional reinforcement, which should be placed on both faces of the panel to resist load reversals. However, the amount of flexural reinforcing should be limited so that tensile reinforcing yields before concrete crushing can occur. Shear steel can help increase shear resistance, confine the flexural reinforcing, and prevent buckling of bars in compression. The mode of failure should be that of the panel itself in flexure and not failure of the connections or a shear failure of the panel.

The 6-in.-thick x 22-ft-tall panels were reinforced with ribs spaced 6 ft apart.

A minimum panel thickness of 5 in., exclusive of reveals, should be designed. The panels also should include two-way reinforcing bars spaced not greater than the panel's thickness to increase ductility and reduce the chance of flying concrete fragments. The thinnest panel thickness acceptable for conventional loads should be used. The objective is to reduce the loads transmitted into the connection, which must resist the panel's ultimate flexural resistance (see Reference 6).

The following features typically are incorporated into precast concrete panel systems to accommodate blast loading:

- Panel sizes should be increased to two stories tall or one bay wide, at least, to increase their ductility. Panels can then absorb a larger portion of the blast energy and transfer less through connections to the main structure.
- Panels should be connected to floor diaphragms rather than to columns, to prevent applying lateral loads to the columns.

- Panels may be designed with integrally cast and reinforced vertical pilasters or ribs on the back to provide additional support and act as beams that span floor-to-floor to take loads. This rib system makes the panels more ductile and better able to withstand an external blast, but it also forces the window fenestration into a punched-opening symmetry.

Loadbearing precast panels must be designed to span failed areas through arching action, strengthened gravity connections, secondary support systems, or other ways of providing an alternative load path (see Reference 7).

Connection Concepts

Precast concrete wall-panel connections for blast-loading conditions can be designed as strengthened versions of conventional connections, with a likely significant increase in connection hardware. They also may be designed as connection details that emulate cast-in-place concrete to provide building continuity.

For a panel to absorb blast energy and provide ductility while being structurally efficient, it must develop its full plastic-flexural capacity, which assumes the development of a collapse mechanism. The failure mode should result in yielding of the steel, not the connection splitting, spalling, or pulling out of the concrete. This means that structural steel connection material must be designed for 5% to 10% more than tensile and yield strength. The connection's shear capacity also should be at least 20% higher than the member's flexural capacity.

Steel-to-steel connections should be designed so the weld is never the weak link in the connection. Where possible, connection details should provide redundant load paths, since connections designed for blast may be stressed to near their ultimate capacity, and the possibility of single-connection failures has to be considered. The number of components in the load path and the consequences of a failure of any one of them will also be a factor.

The key concept in the development of these details is to trace the load or reaction through the connection. This is more critical in blast design than in conventionally loaded structures. Connections to the structure should have as direct a load path as practical, using as few connecting pieces as possible.

It is also important that connections for blast-loaded members have sufficient rotational capacity. A connection may have sufficient strength to resist the applied load, but when significant deformation of the member occurs, this capacity may be reduced due to rotation of the connection. Both bolted and welded connections can perform well in a blast environment if they can develop strength at least equal to that of the connected components (see Reference 8).

(For details on key connections used in precast concrete designs, see Chapter 4C "Connections.")

References:

1. DN-14-04: *Designer's Notebook: Blast Considerations, Introduction*, p. 2.
2. DN-14-04: *Designer's Notebook: Blast Considerations: Blast Basics*, p. 3.
3. DN-14-04: *Designer's Notebook: Blast Considerations: Blast Analysis Standards,* pp. 5-6.
4. DN-14-04: *Designer's Notebook: Blast Considerations: Standoff Distance*, pp. 13-14.
5. DN-14-04: *Designer's Notebook: Blast Considerations: Design Concepts*, pp. 14-16.
6. DN-14-04: *Designer's Notebook: Blast Considerations: Architectural Precast Concrete Cladding*, pp. 19-20.
7. DN-14-04: *Designer's Notebook: Blast Considerations: Architectural Precast Concrete Cladding*, pp. 19-20.
8. DN-14-04: *Designer's Notebook: Blast Considerations: Connection Concepts and Details*, pp. 21-24.

Resources:

DN-14-04: *Designer's Notebook: Blast Considerations.*