Precast Inherently Provides Resiliency

High-performance structures are enhanced by the inherent benefits provided by precast concrete, such as storm protection, seismic, blast and fire resistance, and acoustic control

— Craig A. Shutt

In recent years, building owners have become more aware of the dangers posed by natural and man-made forces that can impact their tenants and structures. Designers must increasingly take into account factors such as harsher and more frequent storms and terrorist threats when designing all types of structures. To meet these needs, they often turn to precast concrete structural and envelope systems, as they provide inherent protection against multiple hazards.

Natural Forces

Precast concrete designs offer protection against such natural disasters as storms and floods, earthquakes, hurricanes, and tornados or other high-wind situations. Considering these benefits early in the design process, and working with a precaster to understand the material's capabilities, maximizes precast concrete's effectiveness against each of these events.

High winds pose two threats: the wind load itself and flying debris, which essentially become projectiles or missiles that travel at speeds of more than 100 mph. It's the second threat that does tremendous damage as envelope systems are compromised. Precast concrete's ability to protect against wind-borne debris has been well proven in independent tests. Precast's strength and durability also provides protection against storm surge resulting from a hurricane.

Precast structural components can also be designed to resist seismic forces and remain standing after even the most severe earthquakes. Extensive research has been done on unbonded, post-tensioned precast shear wall and hybrid moment frame systems. Several of these concepts have been adopted into standards such as ACI-318 which is referenced by the International Building Code. These options allow designers to meet seismic-related design challenges, in most types of buildings nationwide.

Precast concrete structural systems also can help restore a building to full functionality with minimal labor and resources after a major event such as an earthquake or hurricane. This capability helps minimize negative effects to the environment due to reduced reconstruction and downtime, since resilient structures do not need to be completely rebuilt.

Man—made Forces

Buildings also need to resist a variety of man-made forces, such as fires and explosions. Whether improving blast protection for any building or meeting specific Anti-Terrorism/Force Protection requirements for government buildings, precast concrete can provide the needed design attributes. Durable architectural precast concrete panels can mitigate shock waves, connections in structural precast concrete can protect against progressive collapse, and decorative precast concrete barriers can protect the building's perimeter.

High-performance precast concrete also protects against fire and fire suppression damages. Its inorganic composition ensures it will not combust, providing passive fire protection. That allows it to easily achieve required fire ratings, slow the spread of fire, remain structurally intact, and allow reuse of the panels afterward. Precast concrete is also less damaged from sprinkler activations and fire department actions to bring a fire under control.

Other indoor environmental quality (IEQ) benefits can also accrue from precast concrete's attributes. It prevents mold growth, protects construction materials against moisture through faster construction, and eliminates the need to add drywall to interior walls. It also does not need additional treatment to provide adequate sound insulation to achieve required sound transmission or impact-insulation class ratings due to its density.

High-performance precast concrete offers owners and designers many benefits to help create a safe, secure, and productive environment for tenants and building users. The following examples show ways in which precast concrete's resiliency helped meet a variety of owner needs in a wide range of building types often with minimal changes to conventional design.

Architectural precast concrete panels inset with a terra-cotta veneer helped the new 172,000-square-foot Public Safety Building in Salt Lake City meet a variety of goals, including aesthetic design, safety, and seismic needs. All photos: The Exoro Group and GSBS.

PROJECT SPOTLIGHT

Public Safety Building

Location: Salt Lake City, Utah

Project Type: Police and fire headquarters

Size: 172,000 square feet, plus 143,000-square-foot, two-story, below-grade parking structure

Cost: $85 million

Project Management: MOCA Systems, Salt Lake City, Utah

Designer: GSBS Architects, Salt Lake City, Utah, and MWL Architects and Planners (McClaren, Wilson & Lawrie Inc.), Phoenix, Ariz.

Owner: Salt Lake City Corp., Salt Lake City, Utah

Structural Engineer: Dunn Associates Inc., Salt Lake City, Utah

Construction Management: Okland Construction Co., Salt Lake City, Utah

PCI-Certified Precaster: Hanson Structural Precast, Salt Lake City, Utah

Precast Components: Insulated wall panels

Public Safety Building

Salt Lake City officials set high standards when they planned their new Public Safety Building. The four-story facility needed to house police and fire facilities, central dispatch, emergency operations, and a state-of-the-art media-communications center.

As the center for first responders in an emergency, the building had to protect against both natural and man-made forces that could disrupt response time. This required designers to build in fire, blast, seismic, and other protections while also creating a welcoming facility for visitors. The building also had to achieve high LEED standards, with a goal of becoming the first public-safety building in the country to achieve Net Zero energy use.

To help meet these needs, designers clad the building with insulated architectural precast concrete wall panels inset with terra cotta pieces. The panels not only provided protection and energy efficiency, but also created an aesthetically pleasing appearance.

The 172,000-square-foot building features a sweeping glass façade that curves around a landscaped public entry plaza and festival space. The concave glass curtain wall leans back as it rises, canting in one direction and then the other, sloping from one wing to the other. On one side, upper floors step back, with each level topped with a green roof.

"The combination of energy efficiency and ballistics protection in particular pointed us quickly to precast concrete," says Kevin Miller, president and principal in charge of the project at GSBS Architects. "We also needed a high-performance material that could withstand a 7.5-magnitude earthquake and allow immediate occupancy afterward." That seismic level is well above code requirements even in this stringent region, he notes. "The building serves first responders, and they needed to be ready to help immediately."

The ability of precast concrete to provide dense, thick walls offered the key to the needed ballistic protection, he notes. Designers wanted to ensure that officers were protected from drive-by shootings and other projectiles, with the building's durability intended to discourage them from being fired in the first place. Manufactured with 7,000-psi concrete, the panels consist of 1 3/16 inches of terra cotta, a 3 1/16-inch concrete wythe, 2 ½ inches of rigid polyisocyanurate insulation, and an interior 4-inch concrete wythe.

"That thickness of terra cotta and concrete provides a pretty good deterrent," Miller says. The panels were designed to protect against

high-caliber ballistic penetration, and tests showed that no projectile ever penetrated to the second layer of concrete, much less through it.

The 9-foot-tall by 30-foot-long panels were connected to the columns of the steel structure. They were attached to allow the panels to move with the frame, which is braced with 55 viscous seismic dampers stacked on vertical columns. The panel sizes and weights created no special challenges in connecting them to the frame.

"Our goal was to ensure that the building moved smoothly with a seismic event, so the first responders could get up off the floor after the structure stopped moving, dust themselves off, and get back to work," Miller says. The design's dampers only come into play with a truly massive seismic displacement, he adds. "It won't even notice smaller earthquakes. The fourth story will have a lot of energy to absorb, but the design was created to dampen that effect."

'Our goal was to ensure that the building moved smoothly with a seismic event.'

The thick panels also increase the energy efficiency of the building, providing an R-value of 19. Composite pin connectors tie together the concrete wythes, minimizing thermal bridging. Recycled rebar was used for reinforcement. Designers also intend for the concrete's thermal mass to aid with cooling needs, Miller says. "In the summer, the walls will store the cold air at night and help keep the building cool during the day."

Energy efficiency, as well as the use of recycled materials and minimizing construction waste, were key benefits that precast concrete helped provide. Once it is reviewed, the building is expected to achieve a LEED Platinum rating. The precast concrete panels also helped the LEED rating by being manufactured locally. Other key sustainable-design concepts included on-site rain gardens, saving existing mature trees; incorporating window louvers to direct sunlight, installing high-efficiency lighting, utilizing reflective roof materials, and using low-flow plumbing fixtures.

Aesthetic Design Enhanced

These functional needs were matched by the building's aesthetic design. The designers' goal was to complement the nearby historic city hall's Neo-Gothic design that featured brown sandstone. "The use of terra-cotta tiles embedded in the precast concrete panels allowed us to create a dialogue between the buildings despite the difference in age," Miller says.

The Old-World style of the sandstone's texture was achieved by mixing three colors of terra cotta in random patterns, creating a complementary shade to the sandstone that has a similar uneven appearance. "We wanted a look that was refined, clean, and simple, but also one that spoke to the function of the building through its durability and strength."

The tiles were fired as 1- by 5-foot tiles, and they were embedded into the panels to create a 30-foot grid pattern. That long, narrow size fit into panels that were large enough to make the panelization economical without requiring special connections or design considerations to provide the necessary seismic movement.

"There were concerns that the budget wouldn't be able to accommodate terra cotta, at which point we would have tried a pigmented color for the precast concrete," Miller says. "But the design was standardized sufficiently to keep it economical."

Erecting the pieces posed only one usual difficulty, crane placement had to accommodate the existing mature trees to maintain that sustainable-design factor. Working in an older neighborhood with existing trees required close communication, but resulted in no delays. Large hoisting cranes were used that allowed the cranes to be positioned farther from the building and existing trees than would have been necessary with an open site.

Opened this summer, the public-safety building has met all of the owners' functional goals while providing an aesthetically strong civic meeting place. "The precaster did a really good job in bringing our vision to life," says Miller. "Where the various materials have to interface, the precast concrete is performing well. It was a challenge to match all of the tolerances we needed on these various materials, but they did it."

World War II Museum

The U.S. Freedom Pavilion (aka The Boeing Center) anchors the multibuilding World War II Museum campus in New Orleans, La. The facility, the second of four structures to be built from the master plan, stands tallest at 100 feet, allowing it to dramatically showcase a variety of airplanes and other artifacts from the period. The building features architectural precast concrete panels that were designed to provide a durable, strong appearance while adding storm protection and a long service life.

The building's construction follows the 2012 completion of The Theater Pavilion (aka the Solomon Victory Theater), the Stage Door Canteen and the American Sector restaurant. The Theater houses a 120-foot-wide screen for a 250-seat "4D" (including live action) theater. Both buildings—as well as the Campaigns Pavilion that is nearing completion—are clad with architectural precast concrete panels supplied by the same precaster.

"The precast concrete façade provided a number of features that made it a strong choice," says Bart Voorsanger, principal at Voorsanger Architects PC. The firm won an international competition to design the master plan and architecture for

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The latest addition to the World War II Museum campus in New Orleans, La., the U.S. Freedom Pavilion is the tallest of four structures. It features architectural precast concrete panels that provide a durable appearance while adding storm protection and a long service life. Precast concrete is being used on all of the facilities on the campus, parts of which are still under construction.

PROJECT SPOTLIGHT

U.S. Freedom Pavilion–The Boeing Center

Location: New Orleans, La.

Project Type: Museum

Size: 36,000 square feet

Cost: $21 million

Designer: Voorsanger Mathes LLC (a limited liability corporation comprising Voorsanger Architects Inc., New York, N.Y., and Mathes Brierre, New Orleans, La.)

Owner: The National World War II Museum, New Orleans, La.

Structural Engineer: Weidlinger Associates, New York, N.Y.

Contractor: Woodward Design+Build, New Orleans, La.

PCI-Certified Precaster: Gate Precast Co., Monroeville, Ala.

Precast Components: 253 architectural panels

the museum campus, anticipated to be completed in 2017. The design was divided into phases to ensure funding could be provided as it progressed, create attractive venues for selling naming rights, and allow the museum to adapt and grow as earned income rose.

The concept for all of the buildings' façades combines precast concrete with large expanses of glass and a metal-rib cladding. Each design features its own unique personality and geometry. The Freedom Pavilion features sloping façades consisting of a series of horizontal precast concrete panels created from repeating configurations of trapezoids and parallelograms. The panels are designed without a single 90-degree angle, and with horizontal joints aligned but tapering, and vertical joints running diagonally.

"Precast concrete's ability to be formed into different shapes, angles, and sizes made it the perfect choice for this museum," says Ed Mathes, chairman of Mathes Brierre, which aided in completing production documents and serving in the field. The two firms created a limited liability corporation, Voorsanger Mathes LLC, to serve as architect of record.

The architects' goal in designing the complex façade system was to create a "visually and inherently strong impression that could provide a light, vibrant environment, not a dark one," Voorsanger says. "Too often, war museums are dark and foreboding. We wanted to visually say that this inherently strong country conducted its efforts during the war to liberate and seek the peace."

Precast concrete was an efficient material for this project because the region has many capable precasters who understood the design concept and had no difficulty addressing fabrication challenges, Voorsanger says. "The bids were very competitive, which was important." The bidding process began shortly after Hurricane Katrina hit, which meant an economical design was vital to ensure construction could continue. "It was a difficult time to attract funds."

Value-Engineered Framing

Precast was also instrumental in helping the designers to value engineer the steel framing cost of the project. For instance, the metal framing system was value-engineered after the initial pavilion was completed. For it, vertical tubing was designed to create anchor points for the panels. Due to the variety of shapes and sloping sides, the anchors staggered a bit as they changed vertical position. "We ended up using more steel than

we anticipated, and we had to clean that up," Priola explains.

Working with the precaster, the design was changed for the Freedom Pavilion to create horizontal tubing, which provided more uniform anchoring points, as the horizontal panel edges remained parallel. This also allowed the tops of lower panels to connect to the same anchor point as the bottom part of the upper panels. "This design made it easier and faster to connect the panels, which reduced material and labor costs," Priola explains. "As a result, despite the complicated panel shapes, the installation progressed without a problem."

The connections will withstand high winds that are common in the area, while the precast panels will protect the building from wind-borne debris due to their inherent strength and resiliency. The size of the panels reduces the number of joints and provides a long-lasting façade that requires little maintenance over its service life.

The precast was designed to replicate an as-cast appearance, which required extensive mold fabrication and a super-light pressure blasting with a special blasting media. Panels on the first level also were sealed with an anti-graffiti coating that allows paint and other markings to be erased easily. The museum's name also was cast into the panel on several façades to create dramatic signage that emphasized the building's strength and permanence.

The panels have a typical height of just under 8 feet. They feature skewed ends and legs, with about 23 panels longer than 40 feet and one longer than 50 feet. Due to the unusual patterns, one panel was 45 feet long and 2 feet tall. Panels on the building's edges also feature an 18-inch return to avoid joints on the edges. Casting the irregularly shaped legs in sequential order required a great deal of form shifting and close communication to ensure the proper panels were fabricated when needed. In some cases, full-size templates were printed to ensure the correct detailing.

The erection moved smoothly despite work continuing on the campus in other locations and continual visitor traffic to the already opened Victory Theater. "New Orleans can be a difficult environment for construction," Voorsanger says. "It's a quasi-tropical zone that's far different from northern climates. But the precast system was something everyone was comfortable with."

Work has now begun on the Campaigns Pavilion, adjacent to the Theater Pavilion, which will provide space for exhibits from the original museum. That phase will be followed by construction of the Liberation Pavilion, Special Exhibits Pavilion, parade ground, and Canopy of Peace. Those buildings also will be clad with precast concrete panels following the same design concept.

"We've been very pleased with the quality we received," says Voorsanger. "A surprising benefit was that everyone quickly understood the architectural concept and saw little difficulty producing it. When the contractor feels confident about providing the product you want and can erect it smoothly, they have less risk to account for and can bid more confidently."

'We've been very pleased with the quality we received.'

The museum already has proven successful with local citizens and visitors, with the second and third pavilions attracting more than 1 million visitors annually and garnering the largest membership of any private museum in the country. "It's been extraordinarily successful," Voorsanger says. "We're extremely pleased with how well it's been received."

Single-Family Residence

A number of residential designers and homeowners are learning the benefits that precast concrete can provide. Bensenville, Ill., resident Kim Olea can't say enough good things about her two-story, 2,000-square-foot home built with a high-performance precast concrete structural system and insulated wall panels.

The home was the first of what was to be a series of residences built by the DuPage Housing Authority to aid residents displaced by expansion at nearby O'Hare International Airport. Ultimately, budget cuts and other economic factors resulted in only one home being built. Olea purchased the home after she left her original home under eminent-domain procedures.

"I watched the cranes building the home, never expecting I'd be living there," she says. "I wasn't familiar with precast concrete, but it's a great house. I feel very safe in it. It's economical to run and environmentally friendly. It's been great."

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The home features 8-inch-thick precast concrete insulated wall panels consisting of 3 inches of polyurethane insulation sandwiched between two 2 ½-inch-thick wythes of concrete. The insulation is bio-based, containing castor oil and soybean oil. The home was enclosed with 21 load-bearing panels, which support insulated precast floor panels to create the structural system.

The 10-inch-thick floor slabs consist of 4 inches of insulation sandwiched between two 3-inch-thick wythes of concrete. These panels also contain radiant-heating tubes that provide the home's heat. Electrical boxes and conduit were cast into the precast panels, as required by local code, and also into the floor panels per the architect's request.

The Housing Authority brought the concept of a total-precast concrete home to architect John Cronin, principal at Number Nine Design in Elmhurst, Ill. "Concrete was perceived as having a number of benefits, especially mitigating sound in this area around the airport, as well as providing durability and sustainability," he says. "The goal was to reduce long-term costs for the homeowners."

This residence in Bensenville, Ill., features a total-precast concrete structural system and insulated precast concrete panels. The home's traditional design belies its state-of-the-art features, such as radiant heating and a highly durable and sound-resistant shell that works well near O'Hare International Airport.

PROJECT SPOTLIGHT

Private Residence

Location: Bensonville, Ill.

Project Type: Residence

Size: 2,000 square feet

Cost: $300,000

Design-Build Team: Number Nine Design, Elmhurst, Ill.

Owner: Private homeowner

Contractor: Gene Orrico, Builder

PCI-Certified Precaster: Dukane Precast Inc., Naperville, Ill.

Precast Components: Twenty-one 8-inch-thick wall panels, twelve 10-inch-thick floor panels

Cronin visited the precaster and was impressed by the concept of sandwich wall panels. "It has a lot of potential but isn't well known for use in single-family residences," he says. "But it worked well with our design concept, which was to keep the home simple and modular while fitting it into a traditional residential neighborhood. Precast would lend itself to a contemporary design, but we weren't looking for that in this case."

The radiant-heating system, consisting of 5/8-inch tubing placed one-foot on-center, will keep the home warm and energy efficient throughout its service life, he notes. "That was a key concern, along with making the home durable and safe." Each floor has its own thermostat, allowing the homeowner more control over energy usage.

The roof was framed out and shingled, and interior walls were framed and drywalled. "We did a lot of planning on the front end to ensure the home seemed traditional, planning the openings and other design details," says Cronin.

The 33 precast components were erected quickly in the four-bedroom home, providing quick protection from the elements and allowing interior trades fast access. "We maintained a traditional layout on a modest size to allow it to be replicated easily."

The homeowner has become a fan of precast concrete. "The radiant-floor heating is the best heat I've ever had in a home," she says. "And the precast concrete walls keep the heat inside very efficiently in the winter. In the summer, the concrete walls keep me nice and cool."

She appreciates the home's other benefits, too. "It's really soundproof, so the planes going overhead aren't a problem," she says. "And I have absolutely no worries about storms, wind, or hail that hit us every so often. I feel like I'm living in a bomb shelter. It's very sound and solid. I would highly recommend this construction to anyone looking for a home."

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Citrus Warehouse

At the other end of the scale, designers and constructors of a $200-million, 640,000-square-foot citrus-packing facility in Delano, Calif., also found the resilient benefits offered by precast concrete components to meet the challenges they face. Its

An aggressive schedule and the need to meet strict hygienic standards led designers at this 640,000-square-foot citrus processing and packaging plant in Delano, Calif., to specify a structural precast concrete system including architectural panels.

PROJECT SPOTLIGHT

Paramount Citrus Packing Co.

Location: Delano, Calif.

Project Type: Citrus warehouse and processing facility

Size: 640,000 square feet

Cost: $200 million

Designer/Contractor: Younglove Construction LLC, Sioux City, Iowa

Owner: Paramount Citrus, Delano, Calif.

Architect and Structural Engineer: Teter Architects & Engineers, Bakersfield and Fresno, Calif.

PCI-Certified Precaster: Midstate Precast, Corcoran, Calif.

Precast Components: 2,100 pieces, including double tees, columns, beams, solid walls, insulated walls, spandrels, plank, stairs, catwalk columns, catwalk beams, and wainscot

high-performance precast concrete structural and envelope systems not only had to meet high seismic requirements and a fast schedule, but also had to provide for the needs of a busy transportation facility and food-processing plant.

The design-build firm, Younglove Construction LLC, had previously worked with the owner's representative, Eric Johnson of Paramount Citrus, on projects undertaken at another firm. Johnson told Younglove Senior Vice President Bill Bradbury to cost out several construction options, including precast concrete. "He likes using precast concrete for food-processing plants, because it provides a variety of advantages that save long-term costs," Bradbury says.

The durable, smooth panels create an ideal environment for sanitary food handling, as they offer no cracks or holes where dirt or moisture can lodge, as well as no way for vermin to gnaw their way in. They also provide long, open spans that make installing large, processing and packaging equipment easier. "A precast concrete interior is smooth, minimizes dust ledges, is easy to clean, and is durable," Bradbury explains. "It's not possible to create such an easily maintained interior with steel."

The designers provided cost estimates for both steel-frame and precast concrete structural systems. The precast concrete design was slightly more costly, but the owner chose it anyway, knowing the benefits it could provide. "He expects that small premium will be well worth it over the building's life through the other savings he will receive," says Bradbury.

Costs were minimized by bringing the precaster into the design process early, Johnson says. "Value-engineering and a partnership with the precaster helped reduce the cost of using precast concrete versus metal. It cost less than 10% more to use concrete, but food safety and longevity of the building increased substantially, which made it the obvious choice to invest in."

The structure features double tees measuring up to 80 feet long,

'Value-engineering and a partnership with the precaster helped reduce the cost of using precast concrete versus metal.'

columns, beams, planks, solid wall panels, and insulated wall panels. A precast concrete hybrid moment-frame system was designed to allow for the reduction in interior structural walls and to meet the high seismic needs in the region.

"An additional reason for specifying the precast concrete system was the aggressive schedule the owner required," says Bradbury. Precast concrete roof-tee construction began four months prior to the start of foundation work, once the column layout was finalized. A key concern was

'An additional reason for specifying the precast concrete system was the aggressive schedule the owner required.'

the need to use the 120,000-square-foot, fruit-conditioning rooms operation, where fruits are ripened. The company's facilities were filling quickly, so that portion of the building had to be completed first and fast.

To meet the schedule, the building was segmented into receiving canopies, conditioning rooms, sorting and packing, cold storage, support systems, and office space. Each space was self-sustaining with its own precast concrete structural system, explains Byron Dietrich, senior partner for structural engineering firm Teter Architects & Engineers. "We didn't build the building linearly or in the most efficient progression for construction needs but rather for the owner's needs in bringing portions of the building online first."

The cold-storage area was created with insulated precast concrete panels 12 feet wide and 40 feet tall. They included 4 ½ inches of rigid-foam insulation sandwiched between a 2 ½-inch exterior concrete wythe and an 8-inch structural concrete wythe and connected with fiber-composite ties. Prestressing strand was used in both the architectural and structural wythes of these panels to prevent cracking. The office portion features steel framing and a limited number of architectural precast concrete panels, due to the complexity of the office structure.

The building's high seismic requirements were met primarily with precast concrete walls and the precast concrete hybrid moment frame. A key challenge came from connecting the panels, due to their 40-foot height and relatively narrow width, Dietrich explains. Hold-downs were placed on every six panels to create expansion joints.

In addition, the building's 450-foot width had to be accommodated without using interior shear walls that would block equipment. Long-span diaphragms were used along the building's length in the direction of the double tees, while the moment frame provided the lateral-resistance in the longer direction. "The system worked well and was easy to construct," says Dietrich.

Providing the number of entry doors for trucks to access the building also posed a challenge, as the entries had to be fit into the building's face with panels arranged to allow for as many openings as possible. "The facility's layout dictated the size and spacing of many of the openings," Dietrich says. Most of the openings were designed to be 13 feet wide and 16 feet tall, with about 3 feet of space between them.

A precast concrete mezzanine and elevated walkway system were added inside the 32-foot-tall building at the 16-foot level. They were constructed with horizontal arms that support planks, with the walls serving as shear and lateral support. "It's a beautiful, simple design," says Bradbury. "The seismic design included the mezzanine, and it makes a great way to not only oversee work in the processing areas but allow people to get to their work stations safely above the forklift traffic."

Roof-level double tees were supported on Cazaly hangers, which replaced corbels that could have retained dust. The hangers are cast into the tees and sit above the roof tee flanges, avoiding the need for lower corbels with dust ledges. "Precast concrete provided a lot cleaner design and works very well for food-processing operations," says Bradbury.

The design created an efficient, cost-effective, and rapidly constructed project. "It was a good project from a team perspective," Bradbury says. "Everyone pitched in to help resolve issues as soon as they arose."

Such an approach ensures that high-performance precast concrete

'Precast concrete provided a lot cleaner design and works very well for food-processing operations.'

maximizes its benefits for a project. As designs become more complex with owners' needs for faster construction, higher safety, aesthetic appeal and other factors, the precaster's input can help ensure that projects remain on time, in budget, and offer a long service life.

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