Hybrid Precast Frame Meets Seismic Challenges

Precast concrete framing system combines high-strength and mild steel to both resist forces and absorb energy, proving superior to monolithic frames in speed, cost and durability

Producing precast concrete structures that meet strict code requirements for seismic conditions has long challenged designers and precasters. But a new design approved for use in western regional codes has proven it can meet the needs while saving time, material and money. In the process, says the team of engineers and contractors who devised it, the design has the potential to alter the fundamental way in which Type I structures are designed and built in regions of high seismic activity.

"Virtually any type of building can take advantage of this connection system," says H.S. Lew, chief of the structures division of the National Institute of Standards & Technology (NIST), United States Department of Commerce. NIST, in a cooperative effort with Charles Pankow Builders Ltd., Altadena, Calif., and the University of Washington, developed and tested the system to determine its performance. The system was designed to Uniform Building Code seismic Zone 4 requirements.

Based on the test results, NIST and Englekirk & Nakaki, Irvine, Calif., developed a set of design guidelines for the use of this system. Using these tests, design procedures, guidelines and other supporting information, this system was accepted after thorough evaluation by the International Conference of Building Officials Evaluation Service (ICBO-ES) early last year.

While Pankow's intent is for unrestricted use of the frame, currently ICBO requires Pankow's supervision for all applications of the frame. "Cur-

The new hybrid precast moment-resisting frame has been put into practice in a parking structure built at Roosevelt Field Mall in Garden City, N.Y. The system was created in a cooperative effort of Charles Pankow Builders Ltd., the University of Washington, and the National Institute of Standards & Technology (NIST).

The new framing design helps the Roosevelt Field Mall parking structure resist wind loads, as there are no special seismic needs required in this region. It also met the owner's desire for open spans unobstructed by conventional shear walls. The project was part of a $150-million capital-improvement program at the mall.

rently, there are highrise structures being designed with this system, as well as parking structures that have been constructed," says Lew. "All types of buildings will benefit, and we expect more will be using it soon, because it should cost less than other conventional systems and speed construction."

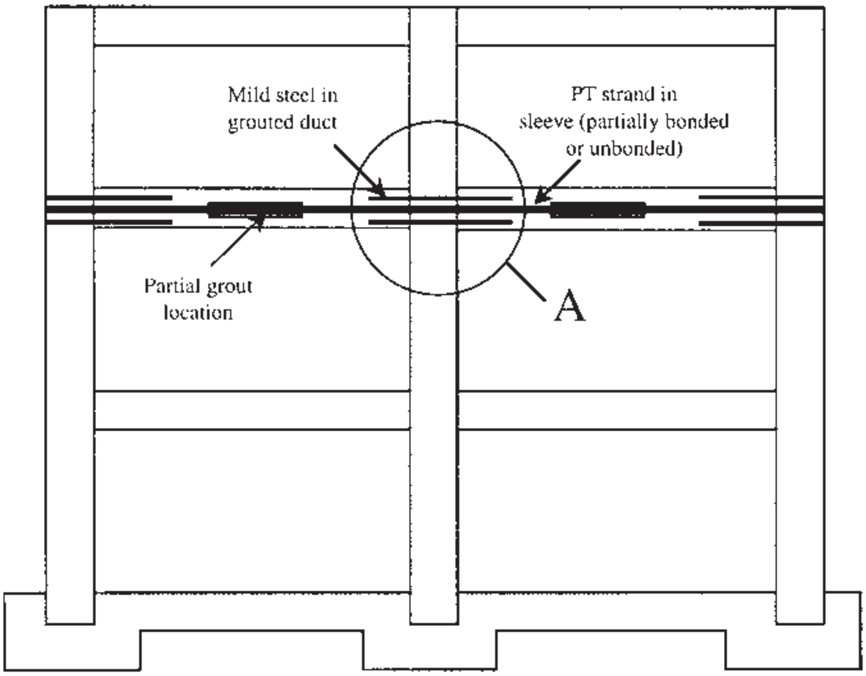
Connection Absorbs Energy

In essence, the system consists of a precast concrete moment frame that absorbs seismic energy in a manner that is independent of the integrity of the structural members, explains David Seagren, manager of research and development at Charles Pankow Builders Ltd., who began collaboration with NIST in 1991. The system's post-elastic performance is concentrated in the connection rather than in a structural member.

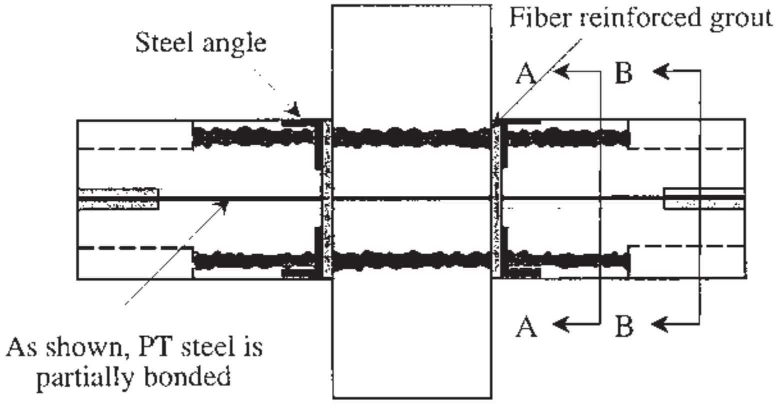
The hybrid frame relies on the connection of its precast columns and beams which use both standard reinforcing steel and high-strength, post-tensioning steel cables to perform two functions. This combination provides both the inelastic action necessary to absorb energy through movement of the joint and the elastic action required to provide the shear and moment resistance that hold the joint together. The high-strength, post-tensioned steel gives the joint its strength to resist applied dead, live, and seismic loads, while the mild steel used across the joint serves as an energy dissipater by yielding under seismic loading, Seagren explains. "It isolates and separates the strength and energy-absorption components within the joint."

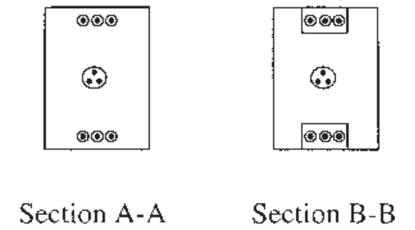
By keeping the initial post-tensioning force low relative to the strand's ultimate strength, the high-strength steel does not yield, staying within its elastic range with a large reserve capacity for deformation. This provides a restoring force that allows the post-tensioning steel to make the joint self-centering, resulting in no residual drift or building lean after a seismic test. "In simpler terms," Seagren says, "the elasticity of the joint allows it to open and close, much like a spring-loaded door, in order to accommodate the seismic ground motion." (For details on how the system installs, see the sidebar.)

The result is a hybrid precast frame that can be constructed economically while exhibiting higher performance than conventionally reinforced cast-in-place concrete frames, he says. Its drift capacity exceeds six percent, demonstrating its reserve capacity, he adds. Only negligible cracks occurred at this high level, and these closed up again upon the removal of the load, confirming the elastic response of the column and beam elements.



This elevation shows how the combination of mild steel and partially bonded post-tensioned strands run through the connection. *Diagram courtesy of NIST*





This detail shows the angles and locations of grouting for the connection. Column bars have been omitted to provide clarity of the system. Diagram courtesy of NIST

Better Than Monolithic

"The new precast frame proved to be at least equal to the monolithic frames in almost all respects, and superior in most," says Geraldine S. Cheok, research engineer in NIST's building and fire research laboratory. She and two engineers—John Stanton, professor of civil engineering at the University of Washington, and William C. Stone, senior research engineer at NIST—described the details of the studies they performed and their design implications in a paper released this spring. (For details, see "A Hybrid Reinforced Precast Frame for Seismic Regions" in the March/April 1997 issue of *PCI Journal*.)

'The result is a hybrid precast frame that can be constructed economically while exhibiting higher performance.'

Others who have participated in reviewing and testing the system also have been impressed with its potential. "The precast hybrid frame uses traditional materials in a unique way that vastly improves both the reliability and performance of a building constructed with this system," says Suzanne Dow Nakaki, president of Englekirk & Nakaki Inc. "This benefits not only building owners but the occupants and users of the building also." Adds Stanton, "The technical innovation is a remarkable break-through."

How It Installs

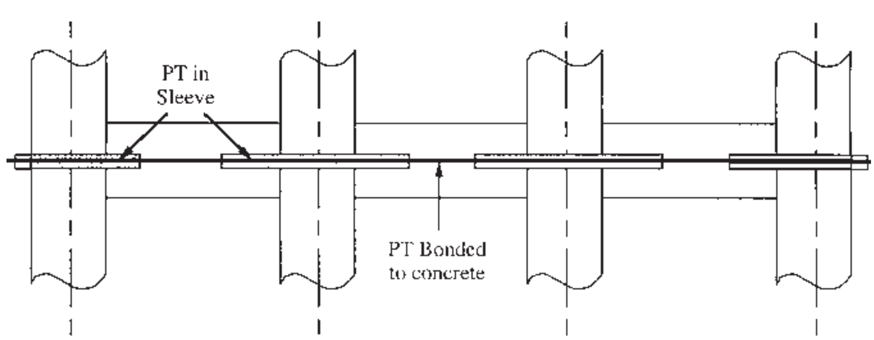
The hybrid connection system is described in detail in a paper presented in the March/April issue of *PCI Journal.* It is authored by John Stanton, professor of civil engineering at the University of Washington in Seattle; William C. Stone, a senior research engineer in the Building & Fire Research Laboratory at the National Institute of Standards & Technology (NIST) in Gaithersburg, Md., and Geraldine S. Cheok, a research engineer at NIST.

A key appeal of the system comes from its use of precast beams and columns without the need for permanent corbels, the three explain. The column is assumed to be a single, multi-story unit to save the cost of splicing. The beam has a solid, rectangular cross-section at its ends and a trough at the top and bottom in its central region. The beam-to-column connection is made with grouted reinforcing bars and post-tensioning that is either partially or totally unbonded. The bar steel is placed in ducts at the top and bottom of the beam, while the straight post-tensioning tendon is located at the beam's mid height.

In the construction sequence, the columns are erected first and are equipped with temporary steel corbels on which the beams will be set. The beams then are erected, and the reinforcing bars are placed in the trough. The bars then are passed through the ducts in the solid ends of the beam, which line up with matching ducts in the column. The gap between the beam and column then is grouted with a fiber-reinforced grout. The ducts containing the reinforcing bars may be grouted at the same time.

When a line of beams is in place and the grout at the beam-to-column interface has gained strength, the post-tensioning steel is installed and stressed. The temporary corbels are removed and the floor system is then installed.

The intent of the system is to have the beams and columns act as rigid bodies, with the deformation of the system concentrating at the beam-to-column joints. The end of the beam rocks against the column face and a single crack opens there. The post-tensioning remains elastic through story drifts of 3.5 percent due to debonding and to the location of the post-tensioning steel.



This diagram of the partial bonding of the post-tensioned strand shows how the system works within the building's frame. Diagram courtesy of NIST

Key Advantages

The system offers owners and designers a host of advantages over other systems, including providing another option when deciding among fundamental building materials with which to build. Others include:

• **Lifecycle costs:** "Long-term costs of the system offer a quantum improvement over other systems," says Seagren. Following earthquakes, a structure using a precast frame constructed with this process will require only normal inspection and minimal, if any, repair of structural members, he says. That's a dramatic change from what typically is experienced following a seismic disaster. For instance, after the Northridge, Calif., earthquake, a relatively minor seismic event, it was revealed that conventional steel moment-resisting frames experienced widespread brittle failure, encompassing more than 100 buildings. Repair costs averaged more than $10,000 per joint. In addition, some severely damaged concrete-frame buildings were demolished due to prohibitive repair costs. "The precast moment-resistant frame results in a building whose value and usefulness is not diminished or decimated by a seismic event," Seagren says.

• **Simplicity:** "The beauty of this new technology is that it is quite transparent to the designer, simplifying thorough understanding," says Nakaki. "The science behind the system requires that the designer truly understands the expected post-elastic performance of the system. This is knowledge that is deeply hidden in the intent of the prescriptive sections of our existing building codes for other types of system."

'Long-term costs offer a quantum improvement over other systems.'

The system is so basic and easy to construct, Seagren adds, that cost savings result when it is used instead of other existing systems. For example, in one recently constructed parking garage, savings were estimated at approximately one percent of the total constructed cost, with a 60-percent savings over the number of man-hours that would have been needed to construct a conventional lateral-bracing system. "These savings, achieved by the new frame, will only increase as its construction techniques are perfected."

• **Speed:** Savings also are expected to mount from the reduced time needed to install the system over conventional systems, Seagren notes. A recently completed 550,000-square-foot, 1,719-car parking lot used the system and was erected in six and one-half months, compared to an estimated 12 months to finish it with a conventional system. That resulted in a 45-percent savings in project delivery time, bringing the structure on line quicker and generating revenues faster, in addition to cutting time on construction loans and labor costs.

• **Safety:** Perhaps best of all, the system's toughness and resiliency helps

Several advantages are offered by the hybrid system, which combines standard reinforcing steel with high-strength, post-tensioning steel cables to provide both inelastic flex to absorb energy and elastic action to offer shear and moment resistance. The benefits include long-term cost efficiencies, simplicity of design, speed of erection and safety enhancements.

protect occupants during a seismic event. "It can significantly reduce structural and architectural damage to new buildings that use the framing system in eathquake zones," says Neil M. Hawkins, professor of civil engineering at the University of Illinois at Urbana-Champaign, who watched the system develop.

In parking garages, it also aids day-to-day security and attractiveness of the property for security-conscious patrons, adds Charles H. Thornton, principal in Thornton-Tomasetti/Engineers in New York City, which helped test the system. "Using this precast moment-frame joinery system in a parking structure provides the additional benefit of offering lateral load resistance under wind or seismic loads while supplying an open plan, free of shear walls," he explains. "This significantly enhances the security of the parking garage."

The use of the system in a recent project resulted in a 45-percent savings in delivery time.

Wide-open spaces can be achieved in parking structures with the hybrid system because it offers lateral load resistance under wind or seismic loads while supplying an open plan free of shear walls.

Designers Tough To Convince

Convincing designers and engineers to adopt the system and achieving code approval proved tough challenges, notes Seagren. It's a process that will continue for some time. "Current codes and design procedures for seismic zones are predicated on structures protecting themselves by dissipating seismic energy by inflicting damage to themselves during post-elastic response," Seagren explains. "While this goal has been largely successful, the impact of severe damage inflicted upon structures by major seismic occurrences has been devastating."

That attitude is beginning to change, as building owners, designers, insurers, and investors realize how devastating such an approach can be. "Structural solutions that minimize the damage or destruction of the structure itself are being focused on," Seagren says. "But solutions have been expensive and very complex technologically." In addition, he says, "engineers who have grown up with

Expert Reactions

Charles Pankow Builders Ltd. has nominated its precast hybrid connection system for the 1997 National Medal of Technology awarded by the President through the Office of Technology Policy. In its supporting background, Pankow submitted the technical opinion of a number of engineers and other experts. Here are some of their comments on the system:

- "Pankow's forward thinking on new ways of construction has led to innovative systems that will revolutionize the precast concrete industry."
  — H.S. Lew, chief of the structures division, National Institute of Standards & Technology

- "Four aspects of this achievement make it unique and deserving of this award. They are the technical innovation, the regulatory difficulties that had to be overcome, the economic success, and the teamwork required to pull off the whole venture."
  — John Stanton, professor of civil engineering and director of the Structural & Geothermal Engineering & Mechanics program, University of Washington

- "This system has very special relevance to our industry in light of the widespread failure of the 'tried and true' steel Special Moment Resisting Frame during the Northridge earthquake."
  — Charles H. Thornton, principal, Thornton-Tomasetti/Engineers

- "While most of the construction industry continues to look for ways to make buildings cheaper, Pankow has been able to incorporate a new technology in a cost-effective way that also significantly improves seismic performance."
  — Suzanne Dow Nakaki, president, Englekirk & Nakaki Inc.

- "One of the big roadblocks to encouraging privately funded research and development in building structures and civil engineering in general is that it is extremely difficult for a sponsor to exclusively capitalize on a successful result. In this case, Pankow has chosen to allow its R&D results to inure to the public domain."
  — Norman L. Scott, chairman, The Consulting Engineers Group Inc.

and lived with codes have these innate preferences for continuing to do what is codified and not to venture into new territory. Overcoming the resistance of a profession, both codified and personal, has not been trivial."

Present building codes discriminate against discretely jointed precast frames for high-seismic zones, explains Norman L. Scott, chairman of The Consulting Engineers Group Inc. of Mt. Prospect, Ill. "Most of the prior technical-development work has been focused on monolithic cast-in-place concrete frames with the intention of having rotation occur in energy-absorbing hinges in the beams some distance away from the column face," he says. "It is not very economical to emulate monolithic-frame behavior with a precast concrete design. Still, up to this time, the codes have tended to force precast concrete in this direction, so many designs have employed cruciform elements that are expensive to cast, ship and assemble."

Adds Nakaki, "In an industry such as ours, where building owners possess relatively little knowledge about the risks of natural hazards such as earthquakes, it is extremely difficult to even attempt innovation that improves performance, much less make it successful as you move across the country."

10 Years Of Tests

The development of a precast moment-resisting frame began in 1987 when the National Institute of Standards & Technology (NIST) started an experimental program on precast beam-column connections subjected to cyclic inelastic loading. The program was conducted with input from a steering committee consisting of individuals from academia and the private sector. Several papers, reports and presentations resulted from this effort.

In the last phase of the test program, a cooperative effort between NIST, Charles Pankow Builders Ltd., John Stanton of the University of Washington, and John A. Martin & Associates, dealt with the concept of a hybrid system that combined the use of high-strength steel and mild steel. Funding for this phase of the program was provided by NIST, Charles Pankow Builders Ltd., and the Concrete Research & Education Foundation (ConREF) of the American Concrete Institute (ACI).

Three potential designs were investigated in 1992-1993 at NIST's laboratories. Two of the designs were developed by NIST and one by John Stanton with Charles Pankow Builders supplying constructability review. Of the three designs, the one identified as having the most potential was further refined and simplified in a follow-up cooperative effort.

"This paradigm shift of combining both elastic action for resistive strength and inelastic action for energy dissipation proved to be a critical development in the success of the new hybrid frame," says Pankow's Dave Seagren. Four test specimens were fabricated under field conditions and tested in 1993–1994 as part of this effort.

Theory In Action

To prove the system would work in actual field conditions, Pankow began construction on a structure using the system in early 1995. In the first of three projects built as part of a $150-million capital-improvement construction project at Roosevelt Field Mall in Long Island, N.Y., Thornton-Tomasetti/Engineers designed a parking garage that incorporated the system, which fulfilled the owner's desire for a clear and open plan that was unobstructed by conventional shear walls.

Moment frame members consisted of 18" x 24" columns and 18" x 36" beams with a maximum contiguous multiple frame length of 90 feet. "The completed structure demonstrated the constructability of the system," Seagren says. "It also confirmed the anticipated favorable cost and schedule impacts."

Successfully taking the project from theory to the field represents a major step that Nakaki hopes is the beginning of a continuing trend. "Design engineers, as a breed, are hesitant to embrace new technology, as it requires them to take risks many are unwilling to take," she says. "It is a major accomplishment not only to succeed in obtaining regulatory approval through ICBO, but more importantly to achieve the approval of many different design firms across the country now willing to professionally stand behind the concept."

Certainly, Seagren anticipates the system will grow in use as its implications become better understood. "The hybrid frame's ability to control damage is a major improvement over previous seismic design approaches," he says. "It will have a dramatic impact on the construction industry worldwide. In addition to the development's remarkable performance, the new system opens the way for the use of precast in seismic regions, with its attributes of economy, high quality and speed of construction." ■

— Craig A. Shutt

The connection system opens new possibilities to designers because it will make precast concrete constrution in high-seismic zones faster and more economical.