The Domino Sugar Refinery residential development in Brooklyn, N.Y., features a number of new buildings as well as renovation of the original building. Gate has cast 993 wall panels using 3-D printed window blockouts to speed its fabrication of pieces for a 42-story residential building in this rendering. Photo: Gate Precast.

3-D PRINTING

3-D Printed Forms Expand Design Options

Printing precast forms with carbon-fiber-reinforced ABS polymer offers durability, high quality, and added intricacy—if designs and costs can be optimized

By Craig A. Shutt

Three-dimensional (3-D) printing has revolutionized many manufacturing processes, producing components quickly and precisely for industries such as healthcare, automotive, aviation, and the military. Now, precast concrete producers are testing the concept to create forms for casting components, and the first applications offer considerable benefits in the right circumstances.

"This could represent a real turning point in the industry," says Mo Wright, marketing director at Gate Precast Co., based in Jacksonville, Fla. The precast concrete producer has taken the lead on evaluating 3-D printed forms, running tests on a complex ornamental piece, and then using them to produce window blockouts in 993 precast concrete panels for a major project.

The 3-D process involves printing the mold from 3-D building information models programmed into a Big Area Additive Manufacturing (BAAM) machine from Cincinnati Inc. The one used by Additive Engineering Solutions (AES) in Akron, Ohio, which produced many of Gate's forms, outputs up to 80 lb per hour in sizes up to 12 × 5.5 × 6 ft. The pieces are built using acrylonitrile butadiene styrene (ABS) thermoplastic with a 20% mixture of chopped carbon-fiber threads, a typical mixture for these pieces, to add durability. They were machined to final dimensions on AES's Quintax five-axis router. ▶

ORNL STUDY WAS CATALYST

The concept of 3-D printed molds for concrete applications began with the Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tenn., which is in the third year of a five-year research program with PCI to determine how new technologies can improve the thermal efficiency of buildings. These have mostly focused on technologies for improved insulated panels.

ORNL has worked for some time with 3-D printing concepts, and codeveloped the BAAM machine. As part of the program in which Precast/Prestressted Concrete Institute (PCI) participates, researchers evaluated 3-D printing concepts for its potential. "We didn't know if it could be made to work in the industry, but we thought it was worthwhile to examine the potential," says Diana E. Hun, a research and development staffer at ORNL.

ORNL consulted with its program's advisory group from PCI, requesting details of a component to test the concept. At the time, Gate was pursuing a Nordstrom project near Columbus Circle in New York, N.Y., that featured an elaborate façade. Gate sent details of one of the cornices to ORNL, which consulted with Tru-Design of Knoxville, Tenn. That firm in turn worked with Thermwood of Dale, Ind., to use its large-scale additive manufacturing 3-D printing and computer numerical control routers to produce a 1-ft-wide segment of a much longer cornice shape for the building.

"We were looking for a project to test the concept on," explains Steve Brock, senior vice president of engineering at Gate and a member of the PCI advisory team for the ORNL project. "We had evaluated it in theory, and we wanted to take it to the next level and create essentially a mock-up to see if there were any issues we overlooked."

Concrete was poured in the mold to create the intricate, rounded facets and sharp edges of the cornice's face. Gate cast 40 concrete pieces

Advanced Engineering Solutions printed some of the forms for the Brooklyn project for which ORNL initially worked on designs. Photo: AES

MANY BENEFITS TO 3-D

Gate's team found significant benefits to the 3-D printed molds. "3-D printing is just another tool we can use, but it creates molds that perform really well," says Wright. "They're extremely durable, easy to manage and handle, easy to repair, fast to create, and able to produce a very high-quality product."

Durability is the chief benefit, all agree. The combination of ABS polymer and carbon-fiber reinforcement creates high resiliency that allows the forms to be reused many more times than with other materials. "We can easily get more than 100 casts from one mold, compared to only a dozen or more from wood or fiberglass molds," says Wright.

On its first project to use the molds in real time, a new mixed-use building on the grounds of the former Domino Sugar Refinery complex in Brooklyn, N.Y., one 3-D mold is expected to be used for 210 pours to create window blockouts for panels.

"The project required many different shapes and sizes of window block-outs," says Brock. "They're not cookie-cutter openings; they're different widths with undulating slopes and deep recessed windows." The mold inserts had to be durable for up to 200 pours and for multiple moves in the plant. They also had to be rigid to fully consolidate the concrete in the deep vertical pours to reduce bug holes.

"There were so many shapes and sizes that the plant's mold shop would not be able to build all the molds and keep up with the production required," Brock says. "The panels are looking great, with nice looking acid-etched, vertically poured surfaces, and the molds are still holding up well."

Such durability not only can reduce per-piece costs on large, repetitious jobs by spreading the cost of the form over more pieces, but it saves table time needed to change to new forms and keep casting.

"Having a casting table locked up but not pouring while new forms are assembled is costly. Those tables are valuable real estate," explains Wright. "We need to be effective on a 24-hour basis, so the quicker we can change out molds, the faster we can produce pieces. If we can produce a mold in six to eight hours and keep casting with it for hundreds of pieces rather than take weeks to create new molds and then replace them every 15 to 20 pours, we're considerably more efficient."

Dan Juntunen, president/CEO of Wells Concrete in Albany, Minn., agrees. "Architectural bed space is valuable," he says. "It's generally the highest cost per square foot on any project." If they can achieve even 100 pours with a 3-D printed mold—and most seem to provide significantly more—the savings mounts up quickly over one that's replaced every 20 pours. "The 3-D molds allow us to eliminate downtime, compared to losing three or four days overall to replacing and aligning new forms."

Wells is using 3-D printed forms to cast components for Pioneer Hall, a student residence at the University of Minnesota. The panels complement the existing brick walls that remain on the renovated structure. "There have been zero issues with the forms so far," he says. "It's really been bulletproof. There's been a huge savings in reliability in our use to date."

DETAILED DESIGNS POSSIBLE

As Gate's work on the Nordstrom cornice showed, the molds also can create highly detailed pieces that otherwise might not be reproducible. "The 3-D printed molds can create more complex, intricate pieces, which may not be possible to be produced any other way," says Wright.

The 3-D printed molds also have an advantage in hiding joints, notes ORNL's Hun. Typical forms are created with seams where material pieces are joined. "Hiding joints can be difficult by hand and adds several steps," she says. "The 3-D printed form creates a monolithic piece. It needs attention, but it can work better than man-made forms."

Gate's Wright agrees. "Wood pieces have to be nailed, caulked, and resined to create round corners or ensure the joint remains watertight," he explains. "The 3-D printed molds are incredibly watertight, so we can achieve sharp facets with no imperfections. The resulting pieces have an incredibly smooth finish with no transitions apparent."

Wells' Juntunen adds, "The quality of the final pieces definitely goes up with 3-D printing. They are crisp and clean, with no joints or seam lines. We couldn't have obtained the look we got for the Pioneer Hall inset-brick panels any other way," he says. "And they couldn't have gotten a better appearance by doing it with any other material."

ONE DRAWBACK: COST

The one drawback, which will take some time to overcome, is the expense. The polymer material is more costly than other options, so the molds need to be used for components being replicated many times—ideally hundreds of times. That eliminates their use on many projects.

The casting of the wall panels for the Pioneer Hall project featured inset brick surrounding the 3-D printed blockouts that created the window shapes. Photo: Wells Concrete.

This insert (4) was cast by Thermawood for Gate Precast during a test of 3-D printed forms. The piece was set into a larger form to create the intricate face of a 1-ft-wide cornice, to see if it could replicate the actual 30-ft-long cornice installed on a Nordstrom store in New York, N.Y. Photo: Gate Precast.

The overkill is easy to see. If 40 pieces are needed and a $1500 wood form can produce 20 pieces, two sets of wood forms can achieve the goal for $3000. Using an ABS form might cost $9000 but produce 200 or more pieces. But if only 40 pieces—or even twice that—are needed, the ABS form can't be justified.

"Most architectural precast façades we produce are custom-designed," points out Gate's Wright. "It's highly unlikely we'd be able to reuse a form, so producing highly durable forms at a higher cost wouldn't pay off." Wells' Juntunen agrees. "Nothing we do is plug-and-play. Every scenario is different. It's hard to say, here's how we'll use it and how much it will cost until we know more."

But savings are possible. Wells, for instance, was able to save considerable amounts because the profile required for its casting wasn't very deep. "When we realized we could create the pieces with a 4-inch-high profile rather than the 18-inch-high one we'd considered, it made a huge difference," says Gary Pooley, regional sales manager at Wells, who worked on the project.

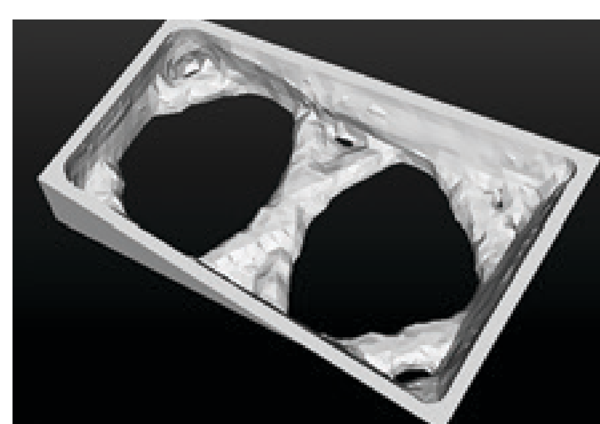
'We need to do more research and experimentation. With more time we can optimize the molds.'

Gate also could have saved if its crew had had more time to refine the design, says ORNL's Hun. "The deadline was so tight to turn around the mold design that we weren't able to optimize it and find ways to decrease the amount of polymer." That not only decreases material cost but takes less printing time. ORNL has since reviewed the design and found significant savings, she noted.

Gate's Brock agrees. "We had one month to complete the design, and it took three tries for us to get what we wanted," he says. "At that point, we took it and ran. We didn't have time to optimize the design, and that would have saved money. There also are less expensive materials to use than 20% carbon-fiber ABS. We need to do more research and experimentation. With more time, we can optimize the molds to reduce what could be a 600% cost difference between ABS and wood."

Brock predicts 3-D printed forms will excel in three applications: high volumes of repetitive and simple commodity pieces, where the ABS molds can be used hundreds or maybe even thousands of times; high volumes of repetitive and complex pieces, where alternatives to ABS would make forms costly to keep creating; and one-time custom pieces that are so complicated or detailed that precast concrete producers cannot afford to tie up their mold-building staff to create for a minimal amount of concrete to pour.

Panels cast with 3D-printed forms were cast in a variety of shapes and sizes to fit the designers' aesthetic goals. Note the blackouts were turned upside down to create a different shape while reusing the same form. Photo: Gate Precast



After the castings began, ORNL went back to try to better optimize the final design its staff created for the window blockouts, with more time to work on it. The design was the final optimized one that could be even more effective, they say. Photo: ORNL

DOMINO SUGAR PROJECT

Gate Precast and Wells can see the potential in the two projects under way. The Domino Sugar Refinery project consists of renovating the massive, 160-year-old refinery building and constructing several new buildings to create a multiuse complex, including a 42-story, mixed-use commercial and residential tower clad with precast concrete wall panels. The tower, 260 Kent, was bid and won by Gate while evaluating the Nordstrom cornice.

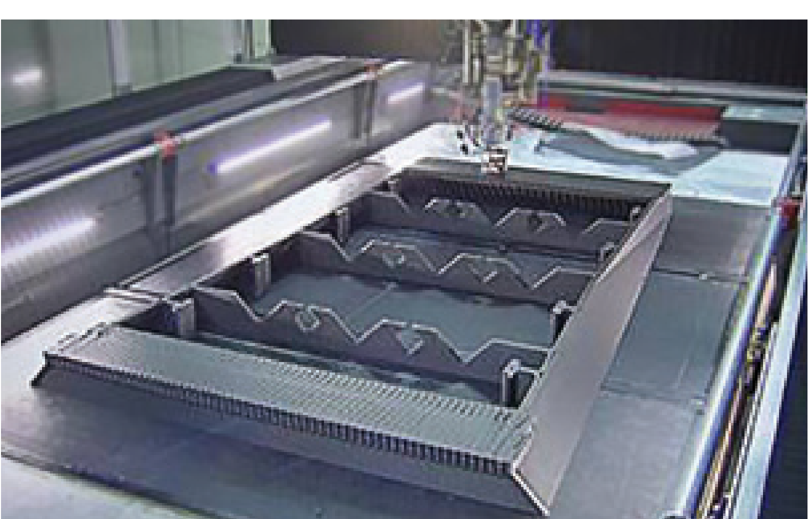
The ABS forms provided the interior sides of window blockouts in various shapes and sizes within the larger panel forms. ORNL produced forms for 20 window sizes and turned 17 over to AES. "We focus on research, not production, so we weren't capable of producing all of the forms Gate required," explains Hun. "We worked closely with AES, exchanging ideas as they arose. There were really no issues or challenges that blocked us."

"Gate and ORNL came to us to see if we could produce more of the 3-D printed molds," explains AES's Andrew Bader, vice president and cofounder. "We saw they wouldn't pose any challenge for our printers." From their end, they were able to optimize some of the molds, he notes. "We cut about 50 pounds from some of the molds, which saved material cost and printing time."

AES's molds were very similar, he adds, but there were a variety of sizes, requiring new molds. This resulted in part due to the varying floor-to-floor heights and the module sizes needed to accommodate the residential interior layouts. Even so, the designers reduced the number of window sizes to boost the number of pieces each mold could cast.

"We went through several iterations of the variation in panels with Gate's input," says Pam Campbell, partner at Cook Fox Architects, the architect on the project. "We looked at how the façade would be panelized and how many modules would be ganged together at each run of façade, based on the crane capacity and transportation limitations. We arrived at a balance that retained the amount of patterning and visual variation in the façade while accommodating the optimized panelization of the modules."

The goal was to maintain the variation in sizes while facilitating repetition, she adds. "Gate really pushed the idea of using the 3-D printed molds, and they ensured we could retain the variation in the façade that was needed while coming up with a cost-effective solution for the molds."



Forms printed with ABS polymer reinforced with a 20% mixture of carbon fibers provide new potential for long-run casts of precast concrete pieces. This mold, printed by the Oak Ridge National Laboratory for Gate Precast, was used as a window blockout inside a panel form for a massive wall-panel project now under way. Photo: ORNL.

The use of 3-D printed molds played to the owner and Cook Fox's concept for the building, she adds. "We have been working with precast panels on several projects over the past eight years, and on this project, we wanted to push our knowledge of the system further and test its limitations. We wanted to create more slender profiles than we have done previously and study a variety of finishes to emphasize the angles of the panel design through light, shadow, and reflection."

The firm's experience with precast concrete panelized systems led them to select it for this project. "We approached Gate specifically due to the variety and level of finishes we wanted in the design."

Even slight changes, by 1 in.—which did occur—required new molds to be produced, notes Brock. "Some of the molds were highly repetitive and gave us a couple of hundred pours, while others we made out of wood because we had to cast only one piece." Some of the 3-D printed mold blockouts were upside-down versions of others, allowing the pieces to be reused while still creating a different window shape.

Gate won the job before it realized that producing the precast concrete panels with 3-D printed molds for a portion of the molds could make it more efficient—if they could make it work. "It was extremely risky, but we realized it was an ideal project to test the concept on, so we decided it was worth the risk," says Wright.

MOCK-UPS TWEAK DESIGNS

A variety of samples were created to show the owner and designers how the 3-D printed molds would work. The team collaborated with Two Trees Management, the development company on the project that also served as general contractor. "Two Trees was very supportive of the importance of mock-ups in this process," says Campbell. "They brought Gate into the project early to allow for iterations of full-scale mock-ups that brought to light changes that we made."

These included even small details, such as the exact location of the drip edge, the depth of the caulk-joint recesses, and the interface of the polished finish and the acid-wash finish. "These were all reviewed and worked out in early mock-ups, so there were no surprises."

The tolerances the designers and Gate required for the project were easily managed, notes AES's Bader. "We're used to doing projects for the aerospace industry, where tolerances are extremely tight. Precast products can require tolerances to 1/16 of an inch or so, whereas aerospace often needs tolerances to 0.02 inch. That made it much easier. Beyond that, the design and engineering for the parts are quite similar to what we do for others."

ORNL helped create the initial form designs and cast several iterations to find the best approach. Photo: ORNL.

PIONEER HALL HOUSING

AES also produced 30 forms for the Pioneer Hall project for Wells. That project renovates and adds onto an existing student residence at the University of Minnesota to create an H-shaped building, with new portions aligning with those built in stages between 1928 and 1932. The goal for the design is to "preserve the character-defining features of the original

The central entry infill area was replaced on both sides of the connecting wall in the H-shaped housing unit. Photo: McGough Construction Co.

building, including its historic red-brick exterior, while gutting much of the interior," explains Brian D. Morse, senior architect at TKDA, the architectural firm on the project.

Wells' panels are being erected in the expansion of the north and south courtyards, with careful attention paid to the inset brick to complement, but not exactly duplicate, the original look. Smoothly finished buff-colored end pieces separate the existing building and the new panels that butt against it, helping to make the transition less jarring.

"Matching the appearance was a sensitive issue," says Morse. The original building featured a Flemish bond brick that was hand-laid, with tolerances that varied in coursing and layout. The new panels maintain a contemporary coursing in colors similar to the original. "Our goal was to create a complementary but distinctly different look to acknowledge the differences."

That was especially apparent in the window surrounds, which in the original building featured wood trim and sill. The new precast concrete windows, which consist of punched windows in the concrete panels, feature surrounds with a different appearance from the originals. They were cast with the ABS forms.

"The use of 3-D printed forms didn't factor into the design," Morse says. "Wells told us about their plan to use them, but that was as far as it went." As it turned out, the forms created smooth joints that wouldn't have been possible with hand-formed joints. "The pieces turned out really nice and crisp."

The forming method likewise had no impact on the construction activities, says Jesse Turner, project manager for McGough Construction, the general contractor. Regardless of how the forms were made, precast concrete provided the most economical answer. "We performed cost scenarios for other options, including precast concrete backup with hand-laid brick, and precast proved to be the most affordable."

McGough worked closely with the design team and Wells to create the most efficient sizes and designs, he notes. "We reviewed design plans and edited them to what would be most efficient. Wells mentioned they'd be using ABS material for the forms, but it didn't impact our plans."

It was Turner's first project using precast concrete panels, and they provided a variety of benefits. "In the end, it was certainly a good decision to use the material. We maintained a high level of quality control, especially on the corner edges. They achieved a nice, soft edge that turned out great. And there were no installation issues."

LESSONS LEARNED

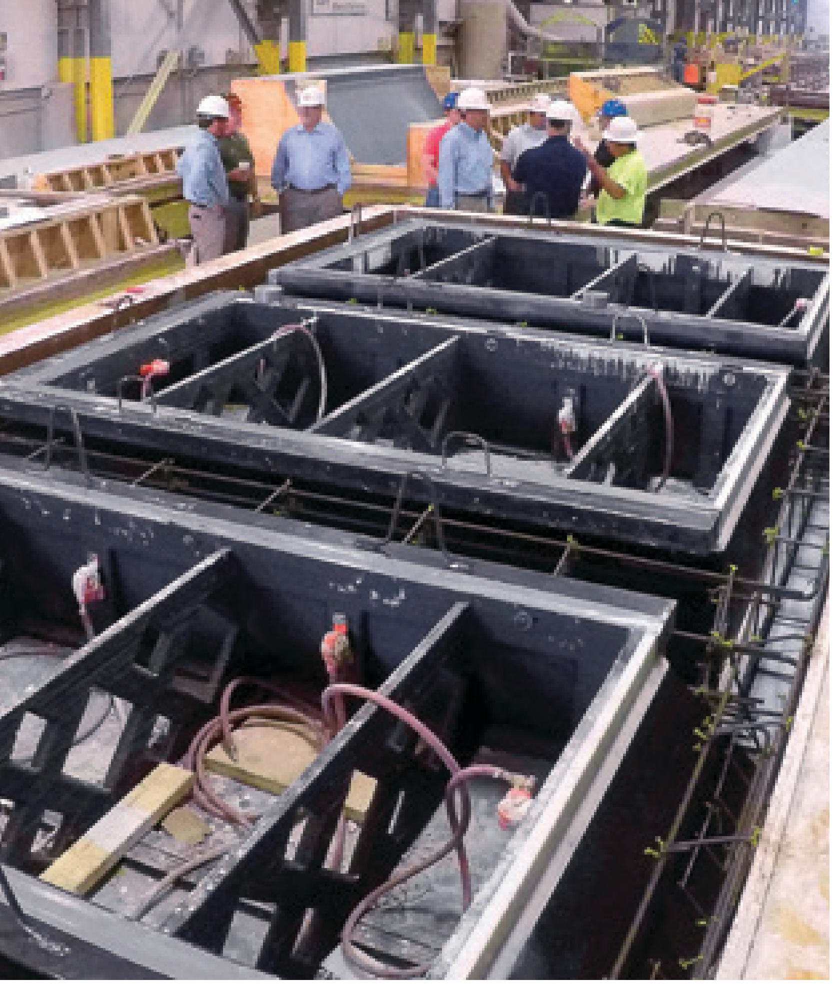
That type of review will help spread the word about 3-D printed forms to both precast concrete producers and designers. "Our hope is that the rest of the precast industry can learn from this work done on the Domino project," says Wright. "Along with PCI, we've hosted a number of tours at our Winchester facility in the hopes that this type of technology will be further embraced."

> 'We started from nothing to try this new technique, and we learned a number of lessons.'

Brock agrees there was a learning curve. "We started from nothing to try this new technique, and we learned a number of lessons." One of those was that added vibrators aren't needed to eliminate imperfections in deep casts. "We had 20-inch-deep pieces, and our vibrating tables worked well. They produced components with no bug holes in a nice, vertical pour with no added vibrators needed."

Another aspect also let them scale back their preventative measures. "We feared we'd need to attach the forms to the pad to prevent them from floating up as the concrete was poured," he says. "But we learned we don't need brackets to hold them down."

Joining the design team early also allowed more input into minor changes that can make a big difference, as with the Domino



Gate's 3-D printed forms were cast by both ORNL and AES owing to the large number and ORNL's limited production facilities. The forms fit inside the larger panel forms to create the window blockouts and were printed on Cincinnati-type machines.
Photo: Gate Precast

Sugar Refinery windows. "When we can work with designers to create more repetitive pieces without diluting their architectural vision, everyone will benefit," says Brock.

AES's Bader agrees. Shallow angles in the forms were initially a challenge, but that was quickly resolved. "Precast producers learned a lot from these initial projects. And while each project is different, there are many lessons that carry over to the next project. The printer doesn't care what shape it's printing or who it's for. Ultimately, we expect we will print most molds that are difficult to construct out of traditional materials like wood or fiberglass, especially if the shapes are complex or have intricate curves or organic shapes."

Gate wants others to learn about the advantages and to benefit from their experience, Wright stresses. "We need more people in the design and precast industries to embrace the material so more pieces are produced, more machines are purchased, more volume is created, and more competition arises. All of those will help reduce costs and make precast more top-of-mind for large, complicated projects."

That doesn't mean 3-D printed forms will become an industry standard soon, they warn. "The shift to using this technique won't be overnight," says Wright. "The setup system will have to change to accommodate these forms, and people will have to be trained to use the equipment and materials. They will have to be integrated into everyone's workflow."

CONTINUOUS IMPROVEMENT

Precast concrete producers also won't rest on their laurels now that they've found initial success. "There may be other materials, such as glass fiber, bamboo, or other plastics, that would create more effective forms," suggests Brock. ORNL's Hun agrees. "It's possible that someday the material could become so durable that these forms could replace steel forms used for standard components if they're damaged. They're less expensive than a new steel form would be."

Certainly, precast concrete producers are looking to use the forms again. "These forms work especially well for large projects with repetitive architectural pieces, and that's our wheelhouse," says Wright. "We often do projects of that size." Adds Brock, "We've estimated more projects with the intent of using 3-D printed forms, and it will not be long before we're utilizing this technology again."

Wells, too, has bid other projects, including a mid-rise building in downtown Minneapolis, Minn., where the intricacies of the design made 3-D molds the best solution. "We can now offer to create any shape that designers want for window accents, along with other features," says Matt Everding, director of operations at Wells. "Keeping the unique designs repetitive helps control the cost. This technique opens a lot of doors for designers. It ensures we can offer them the creativity they are looking for and help take precast to the next level."

'It will take time, but we want to stress that, from a design standpoint, the sky is the limit with these forms.'

It will require an evangelical approach by those who have used the forms. "We need to spread the word through social media, Lunch & Learn programs, meetings, and personal presentations," says Juntunen. "It will take time, but we want to stress that, from a design standpoint, the sky is the limit with these forms. If they have an idea, we can make it happen."

TKDA's Morse has become a believer. "Now that I've seen what they can do with these forms, my next project may be a little funkier."