Masonry Madness

By Cathy Inglis and Jonathon Turley, S.E.

Figure 1. Curved masonry façade.

Brick is one of the simplest and the most versatile materials, one of the most ubiquitous, and often the least regarded.. It is a fundamental staple among building materials, where the small scale and modularity yield enormous potential. Traditional masonry is typified by rectilinear building forms, repetitive laying patterns, and two-dimensional flatness. However, the humble brick is not limited to traditional, and its form can be fluid and sculptural.

The use of brick by renowned architect Frank Gehry challenges the norm with the design of the University of Technology Sydney's (UTS) Dr. Chau Chak Wing Building, School of Business.

This building has been called everything from a treehouse, to a squashed brown paper bag, to a masterpiece. Whatever description applied to it, the Frank Gehry-designed Dr Chau Chak Wing Building is now one of Australia's iconic buildings.

The defining characteristic of this building is its unique masonry façade, which contorts and twists in both vertical and horizontal directions for the full height of the 13-story structure (*Figure 1*). Each brick course snakes along a horizontal plane while vertical curvature is achieved by corbelling each progressive course outward or inward. Gehry chose brick for the exterior to reflect the colonial brick heritage of the surrounding area, curving it to achieve the unique desired form.

Brickwork, at a complexity never seen before, creates a façade that appears to have movement as the horizontal courses of bricks corbel to articulate the building's organic shape.

Although the construction methodology and arrangement of structural elements are like conventional brick façade walls, the wall inclinations and curvatures create structural engineering challenges that are not typically encountered in masonry façade construction.

This drove the development of a custom structural system that included custom brick units, ties, mortar, and construction methods – all designed specifically to cope with the distinctive engineering challenges of the project.

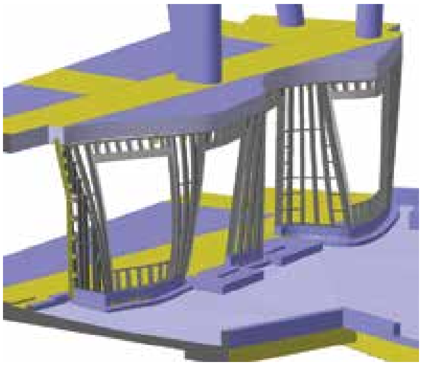

Figure 2. CAD model of curved steel stud wall.

The Façade System

The overall façade system consists of several interconnected components.

The innermost element is a steel stud wall that spans between the concrete floors. Each stud is a curved, T-shaped profile that follows the curvature with the masonry skin in front of it. Since there is no repetition in the masonry façade, every stud wall panel is unique (*Figure 2*). The stud wall is clad with metal sheeting and a waterproof membrane.

Specially designed brick ties bridge a nominal 3-inch (75mm) cavity between the stud wall and the masonry skin. The ties brace the wall out-of-plane, transferring the horizontal load imparted by the masonry wall. The masonry skin itself is constructed from 5 unique brick units developed to achieve the architectural and structural requirements. These were laid meticulously on-site, brick-by-brick. The masonry skin is vertically supported at each level by stainless steel shelf plates which are bolted to the adjacent concrete floor structure. The concrete floor and shelf plate also curve in plan to match the façade geometry.

This arrangement resembles a traditional brick veneer system but functions very differently due to the distinctive geometry.

The Brick-Tie System

Traditional vertical masonry veneer systems resist lateral loads, such as wind and seismic, through a tie system transferring loads to the support system. The ties provide little or no contribution to gravity load resistance, which is transferred downward through the plane of masonry veneer.

This is not the case for the Dr. Chau Chak Wing Building. Each brick is offset from the brick below to create a wall that appears to lean in and out. The offset reaches as much as 1.7 inches (42mm), leaving only 2.7 inches (68mm) of mortar bed joint for the standard 4.3-inch-wide (110mm) brick. Inclinations of this magnitude create significant horizontal loads due to the masonry's weight, which must be carried by the brick ties. This, in combination with plan curvature, creates complex load patterns and concentrations. There is little guidance in the standards on how to deal with this type of loading. It fundamentally goes against the way that masonry is designed and conventionally constructed. When engineering the structural system, the authors had to remind themselves that traditional design and construction techniques could not be applied.

The ties become critical to the stability of the brick façade. They will take significant compression where the brickwork slopes in and tension where the brickwork slopes out (*Figure 3*).

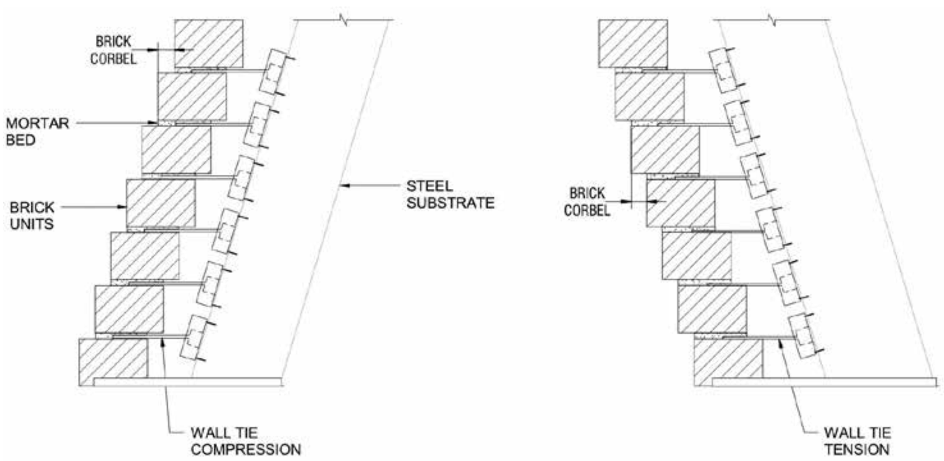

Figure 3. Brick ties in compression when the wall leans in (left) and ties in tension when the wall leans out (right).

The engineers initially explored the possibility of using a traditional metal tie system for the brick façade construction; however, 'off the shelf' ties were found to be inadequate. They are typically embedded in mortar joints and, in this application, would not be satisfactory to resist the loads imposed by the brick eccentricities. It was clear that a more robust brick-and-tie system was required.

In searching for a solution, inspiration was taken from a traditional stone cladding support system in which every stone is supported individually using ties that lock into a groove in the stone edge. The question was: could there be a tie that engaged with the bricks in a similar way?

It is common for brick units to have a localized depression (also known as a *frog*) in the top of the brick to help with mortar bond. A modification of the frog created a continual channel where a tie could be placed. This would provide an internal surface to which the tie could engage and achieve a much higher load-carrying capacity as opposed to merely placing the tie in a horizontal mortar bed joint.

The tie would consist of a threaded rod with a square nut that sat in this channel. The brick tie system adopted is shown in *Figure 4*.

The use of a threaded tie allowed it to be adjusted in and out to suit the channel location, which varied significantly as the façade contorted in plan.

This system was adopted for approximately 35% of the façade area. The remaining 65% consisted primarily of walls with fewer eccentricities. For these areas, a conventional style of masonry tie was adopted since the imposed forces did not require the high tolerance provided by the threaded type tie.

A critical aspect of the design was the vertical spacing of the ties. The goal was to eliminate tension in the mortar joints due to the self-weight of the wall and thus align with a fundamental design philosophy that masonry veneer is not intended to resist constant tensile forces, in line with the Australian and International Standards.

At maximum corbel, over one-third of the brick overhangs the brick below. If two bricks are laid on top of each other at this corbel without any mortar, it is unstable and will collapse under its own weight. The stability of the brickwork relies on mortar to resist tension. By locating a tie at every course in these areas, this localized instability is addressed and the tension in the mortar is eliminated. The spacing was increased to every 4th course where the corbel was less severe (*Figure 5*).

The wall tie is fixed to the stud backup with a special assembly that allows the tie to be adjusted during construction. The tie could be moved up and down and rotated relative to the sloping substrate. The tie could, therefore, be aligned to project horizontally into the brick mortar joints.

Temporary Stability

The question of localized stability under self-weight highlighted another challenge for the design team: the temporary stability of the wall during construction.

An off-the-shelf brick tie system was used for early mock panels but did not provide adequate temporary support of the bricks. They would not engage with the bricks until the mortar had hardened. In areas of significant corbel, it was found that only a few brick courses could be laid at a time before the wall began to collapse. The bricklayers were forced to wait until the mortar had begun to set before proceeding. This not only affected the efficiency of

Figure 4. The custom brick tie system.

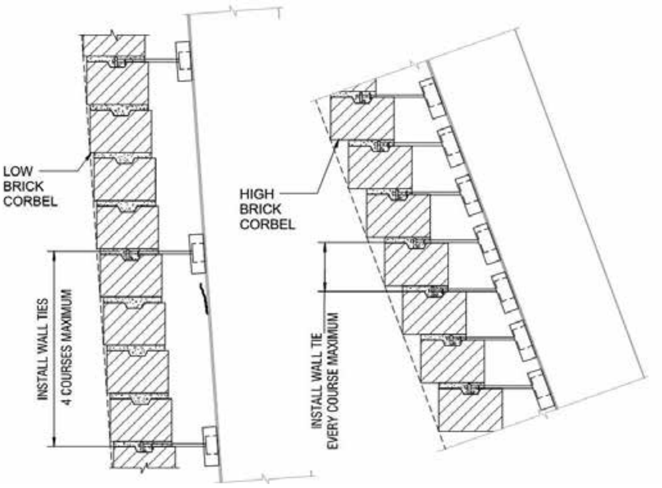

Figure 5. Wall sections showing tie arrangement for a near-vertical wall (left) and heavily corbelled wall (right).

Figure 6. Left to right: centered rebate brick, K brick, offset rebate brick, and L brick.

Figure 7. K brick with rod and tie.

the bricklayers but also may have compromised the mortar bond. This highlighted the requirement for a temporary restraint to the brickwork.

To address this, an additional component was added to the system in the form of a small square nut to be used in areas of high corbel. This can be seen in *Figure 4* on the inside brick edge.

The final solution was a unique structural system developed in collaboration with AECOM Ltd, the façade structural engineer; ARUP, the structural engineers; Lendlease Ltd, the contractor; and Austral Bricks, the brick manufacturer.

The Brickwork

Gehry Partners specified an American manufactured brick with 22 custom shapes to create the unique brick façade. Many trials were undertaken to match the brick, at UTS's request, to manufacture an equivalent brick in Australia. Collaboration between the brick manufacturer and the project architects changed the brick to a standard Australian size (230 x 110 x 76mm), reducing the final number of custom brick shapes to five. Dry press brick manufacturing was selected as that method produces solid bricks and intricate shapes. The corbelled nature of the façade meant all brick surfaces needed "face" finish, as they would all be visible.

There were 380,000 bricks with the 5 custom shapes produced at Austral Bricks Bowral Dry Press Plant just south of Sydney. The custom bricks include the centered channel, the offset channel, the K brick, the L brick (*Figure 6*), and a solid brick without a channel.

The K brick has an angled protrusion to create bends and shadowing appearing as though it has been offset from the standard coursing (*Figure 7*). The L brick is 5.5 inches (140mm) wide and installed at the shelf angles to reduce the size of the control joint from 2 inches to 1 inch (50 to 25mm) and improve the appearance, with the extra width giving sufficient bearing on the angle (*Figure 8*).

Structural Analysis

Detailed finite element analysis was carried out to determine the force in the ties and stresses in the masonry under various load cases (*Figure 9*). The values determined from analysis were later compared to the capacities measured from laboratory testing.

There was a particular focus on the most intricate brickwork panels to identify critical areas and complex behavior.

Laboratory Testing

Throughout the design phase of the system, a series of laboratory tests were carried out to determine the performance and properties of the various components. It was essential to demonstrate the structural adequacy of this completely new system. The brick tie pullout capacity and mortar bond properties were key to confirming the adequacy of the system.

Two full-size mock panels were constructed to evaluate constructability and calibrate the analysis models (*Figure 10*). Strain gauges were fixed to the brick ties, and the panel was tested to failure using horizontal and vertical hydraulic jacks.

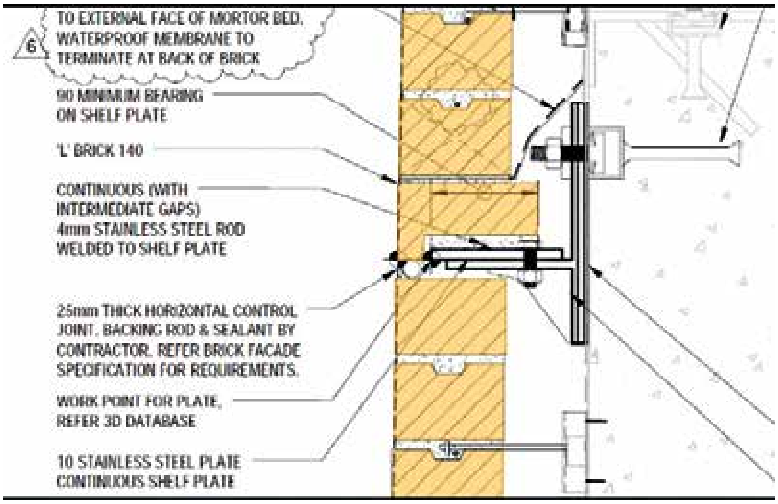

Figure 8. L brick detail.

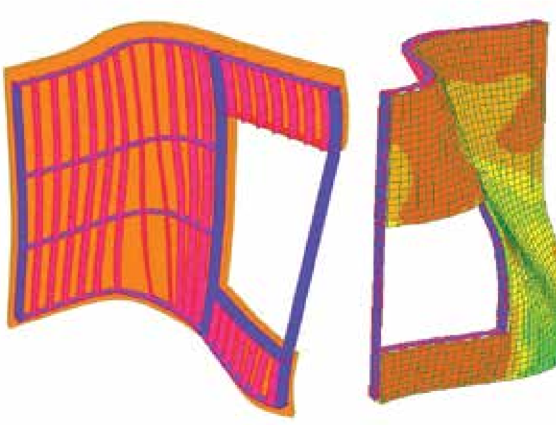

Figure 9. Finite element model of brickwork panel and associated steel substrate (left) and wall stress contour output (right).

Construction

The unique nature of the brickwork created many challenges on-site, with bricklaying production as low as 50 bricks per man per day in very complex areas.

Ensuring consistency of the mortar was crucial. Oven-dried sand was used to enable better control of the water content of the mix. The sand/cement mix was prepared in premixed bags to reduce the chance of error and inconsistency when mixing on-site.

Additives were also premixed in the water in an on-site reservoir to reduce variability between batches. This was trialed as part of mix design testing to ensure the process did not adversely affect the mortar properties. The brick packs were dipped in water for a specified time before laying to reduce the suction and ensure that all bricks had the same water absorption. This was in stark contrast to traditional brickwork construction where a wheelbarrow and a shovel are used to measure out the various mortar ingredients.

Brick cleaning posed another challenge onsite, as typical cleaning acids were not allowed on the project. The suggestion to use a commercial vinegar solution was offered up from a retired bricklayer that had used this method before the introduction of hydrochloric acid.

Through the application of the latest design techniques, the design team pushed the boundaries of what can be achieved with masonry, one of the oldest building materials still in use. The problem was broken down and rebuilt from first principles. Unique and innovative engineering solutions allowed the reinvention of the masonry façade and the realization of Frank Gehry's vision.▪

Figure 10. Full-size mockup panels before load testing.

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