PROJECT CASE STUDY: STRUCTURAL ANALYSIS, DESIGN AND LABORATORY TESTING OF A COMPLEX MASONRY FAÇADE

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ABSTRACT: *This paper is a case study for the structural analysis, design and laboratory testing of the complex façade of Frank Gehry's Dr Chau Chak Wing Building, University of Technology, Sydney, Australia. It presents the design philosophy adopted for the overall brick support system and the final design solution. It also gives an overview of the analysis and design process, and laboratory testing used to arrive at the final solution.*

KEYWORDS: masonry, façades, Frank Gehry, finite element analysis, laboratory testing

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1 INTRODUCTION

The Dr Chau Chak Wing Building, designed by architect Frank Gehry (GP), is currently under construction by the University of Technology, Sydney (UTS). The new business school is part of UTS's City Campus Master Plan and is due for completion end of 2014.

The defining characteristic of this building is its unique masonry façade which contorts and twists in a three dimensional plane for the full height of the 14 storey structure. Figure 1 shows the architect's representation of the brick façade in its early form.

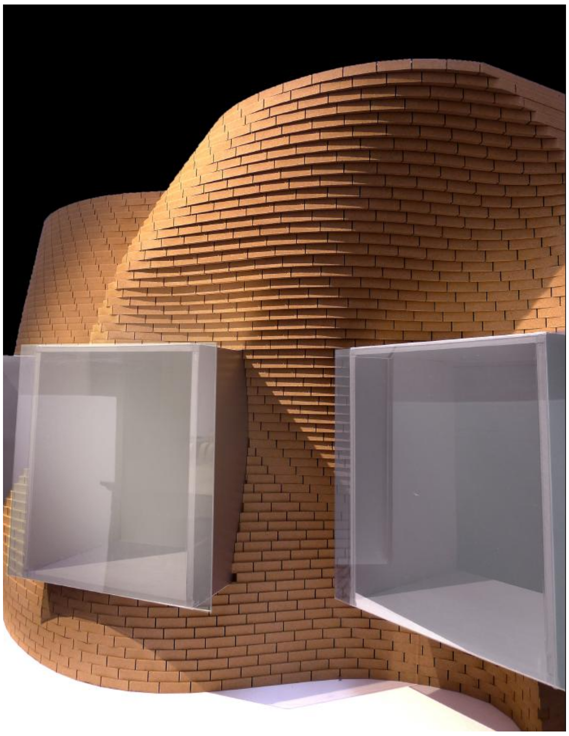

Figure 1: *Early architectural model of a portion of the brick façade*

Although the construction methodology is similar to conventional brick façade walls, the design wall inclinations and curvatures create structural engineering challenges which are not normally encountered in cavity clay masonry veneer façade construction.

These unique engineering requirements drove the development of a cladding support system which included custom brick units, ties, mortar and structural reinforcement. The system was designed specifically to cope with the engineering challenges for this project. The system was analysed using finite element software in conjunction with laboratory testing to validate the structural solution.

AECOM's Sydney-based Structural Engineering team was engaged as the structural designer of the brickwork façade component of the proposed Gehry designed, Dr Chau Chak Wing Building.

AECOM's designers worked closely with the project design team and other associated parties including the main contractor and bricklayers.

The final AECOM design was an innovative structural solution for what is considered by many to be the most complex masonry façade in the world.

2 TRADITIONAL MASONRY FAÇADE SYSTEMS

Brickwork façades applied to multistorey constructions are generally non-load bearing and act as a cladding for the building super-structure. The primary load borne by the brickwork façade is the dead load associated with its own weight which is then transferred back to the super-structure at floor levels. The brickwork may be supported at the slab edge via a shelf plate or built directly off the floor slab. [1].

The typical brickwork façade acts as a weather barrier incorporating an internal wall, cavity and flashing to ensure that moisture does not pass from the external surface to the habitable internal spaces. The internal wall also acts as a structural backing to brace it from out-of-plane loads such as wind, earthquake and maintenance. Steel wall ties are installed to connect the two elements as shown in Figure 2. The ties are generally placed at 600mm centres and within 300mm of any building edge or wall opening [2]. The internal wall is usually blockwork, lightweight steel or timber studs.

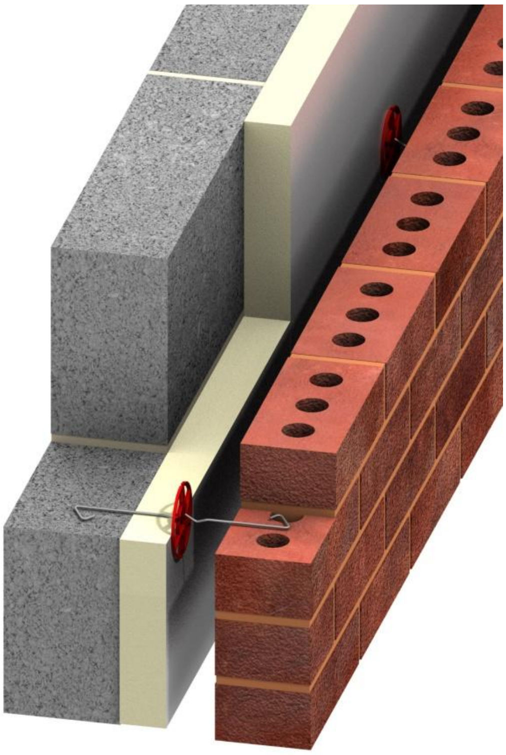

Figure 2: *Typical wall ties connecting masonry façade to an internal structural wall [6]*

The incorrect installation of wall ties was an observed source of structural failure in buildings affected by the 1989 Newcastle earthquake [3]. This highlights the importance of the wall tie as the key structural element for transferring load between the external façade and the supporting structure.

Mortar is a combination of sand, cement, lime and water. Mortar is used as a bonding agent between individual bricks providing strength to form solid walls. The mortar joints between bricks also provide the opportunity for adjustment for variance in the size of brick units [4].

Brick units (in Australia) are in general composed of clay which is moulded (pressed and shaped) with standard dimensions of 76mm (h) x 110mm (w) x 230mm (l). There are variations to this dimension (for example in the case of "modular bricks" which are 90mm (h) x 90mm (w) x 290 (l)) however the mass produced bricks are in the standard dimensions.

The two main brick categories are the dry-pressed and extruded as shown in Figure 3. Extruded are partially hollowed out allowing for mortar joints to infill into the unit while dry-pressed features a frog (indent in the top of the brick). The hollow of the extruded brick and the frog of the dry pressed brick assist with the bedding and bonding between bricks.

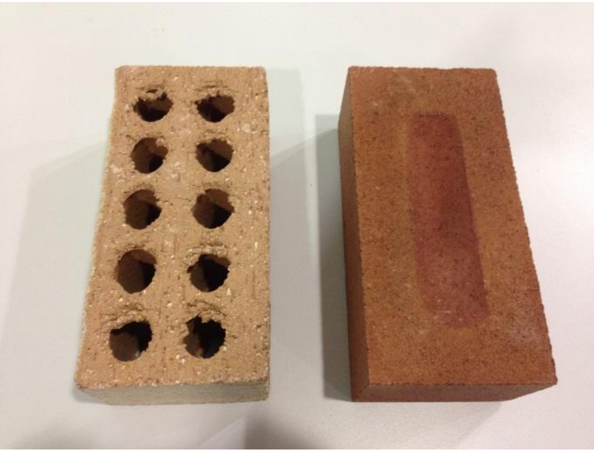

Figure 3: *Typical extruded (left) and dry-pressed brick (right)*

Bricks can be laid in a variety of "bond patterns" including Flemish and English [4] however the most commonly used in multistorey construction is Stretcher. Stretcher bond is laid in an overlapping manner where the vertical mortar joint between horizontally laid bricks is located directly over the middle of the brick unit in the course below.

Brickwork façade failure includes cracking, detachment of units, water ingress as well as catastrophic collapse. Two key sources of failure stem from careless construction processes and façade designs that employ overly complex features that lack support [1].

The traditional system described above is typically applied to vertical brickwork façade walls. For the unique façade of the new UTS building there was a need for the specific design of an integrated structural system.

3 OVERALL STRUCTURAL SYSTEM

The clay masonry brickwork veneer for this building project consists of a non-load bearing masonry skin, supported out-of-plane by wall ties which transfer horizontal load to an interior structural steel frame or substrate. The masonry skin is vertically supported at each level by stainless steel shelf plate which is bolted to the adjacent concrete floor structure.

It was proposed that the brickwork would be laid on-site brick-by-brick in a third running bond pattern using standard size 76x110x230 brick. The vertical slope is achieved by laterally offsetting the position of each brick relative to the previously laid course below (corbelling). The slope of the brickwork reaches 26 degrees from vertical which equates to 42mm of brick corbel with only 68mm of bed joint width using a standard 110 wide brick. We note that a corbel of this magnitude is outside the requirements of Australian Standards [5].

The proposed inclinations and curvatures in the brickwork face create significant out-of-plane dead loads which are not encountered in traditional masonry façade systems under normal gravity loads. As such, the wall ties for the project are in compression where the brickwork slopes in and in tension where the brickwork slopes out. This is shown diagrammatically in Figure 4 and Figure 5. These loadings are in addition to other façade-related loads associated with short-term variable lateral winds, seismic movement and maintenance.

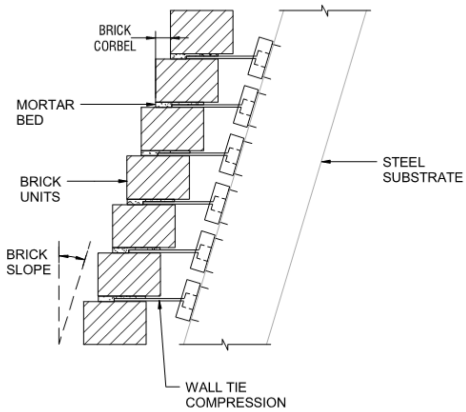

Figure 4: *Section of typical sloping in wall*

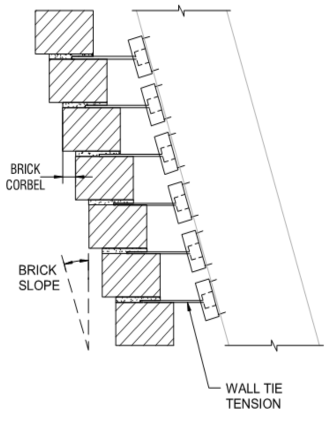

Figure 5: *Section of typical sloping out wall*

As the proposed wall fabric undulates in plan as well as section, the bricks must also be regularly cut to achieve the plan curvature of the wall. Figure 6 shows an area of the constructed brickwork where this was required.

Figure 6: *Plan curvature of brickwork requiring regular brick cutting*

The specially designed and fabricated steel stud frames are constructed to geometrically match the contour of the building. The frames span between floor levels of the concrete framed building. The individually cut curved steel studs are clad with a metal sheet and a waterproof membrane to create the substrate surface. The brickwork is offset from this surface by a nominal 75mm cavity to allow for the egress of water through the brick façade. In constructing the brickwork, it was proposed that the bricklayers use the steel frames as a guide to achieve the design curvature of the façade.

The brickwork is split into panels using vertical and horizontal control joints to allow for brick growth and other movements. The design architectural surface does not contain any regularity and thus no two panels are the same; each has its own distinct contorted shape and edge conditions.

Rectangular window boxes supported by the steel substrate project through the brickwork façade typically at three metre centres.

In conjunction with the design of the support system components, analysis of the brickwork geometry was carried out.

4 ANALYSIS APPROACH

The primary goal was to determine key design parameters such as brick tie forces and wall stresses. These parameters were later correlated with laboratory test data in order to evaluate the performance of the overall system.

Analysis involved finite element modelling of selected brick panels using the Strand7 non-linear analysis solver.

Analysed load cases included maintenance loading, wind, earthquake, brick growth and thermal movements.

There was a particular focus on the most complex brickwork panels in order to identify critical areas and achieve a design solution which appropriately accounts for the worst-case loading scenarios.

The most significant challenge of the analysis was simulating the behaviour of the brickwork such that the key criteria and design parameters which govern the design are modelled appropriately.

4.1 BRICKWORK PANEL

Accurate modelling of the architect’s brickwork geometry was critical to the analysis to ensure any alternate load paths and stress concentrations were considered.

The selected brickwork panel surfaces were directly imported into Strand7 from the Architect’s 3D computer models. The imported geometry was then automeshed using Quad8 plate elements to model the brickwork surface.

The effective thickness of the plate elements was reduced to account for the reduced bedded area of the brickwork in corbelled areas. The thickness was reduced by as much as 38% from the typical 110mm bed width. The material density was adjusted accordingly to ensure the full dead load was considered.

Nonlinear material properties were used to simulate the brittle behaviour of masonry depending on the load case under consideration. The bond strength of the mortar was considered zero under the dead load case. For transient load cases however, the value determined by laboratory testing was used as permitted by AS3700.

4.2 STEEL SUBSTRATE

As shown in Figure 7 the structural steel substrate was included in the analysis of the brickwork to understand the load interaction between the brickwork, ties and steel frame supports.

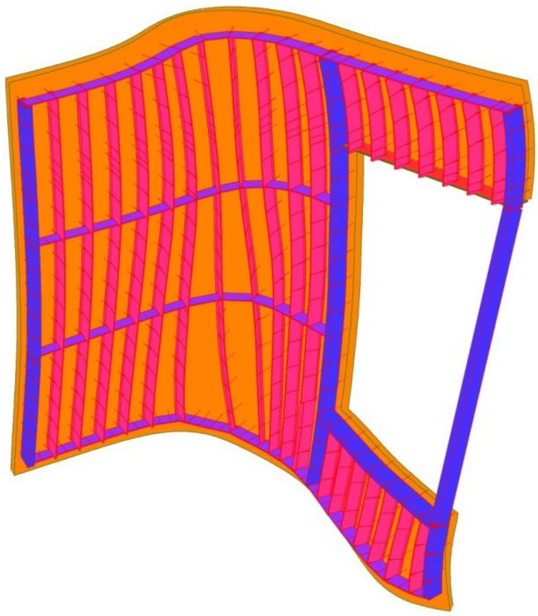

Figure 7: *Finite element model of brickwork panel and associated steel substrate*

The behaviour and relative stiffness of the steel substrate was critical to the analysis of the brickwork.

Generally, an increase in the flexibility of the substrate panel activates alternate load paths and arching which can lead to cracking in the very stiff and brittle brickwork. A stiff substrate is required to minimise this load redistribution in the brick panel.

4.3 WALL TIES

The wall ties were modelled as pin-ended beam elements connecting the brickwork plate surface and steel substrate.

4.4 WALL STRESSES

Figure 8 shows a wall stress contour for a typical panel model.

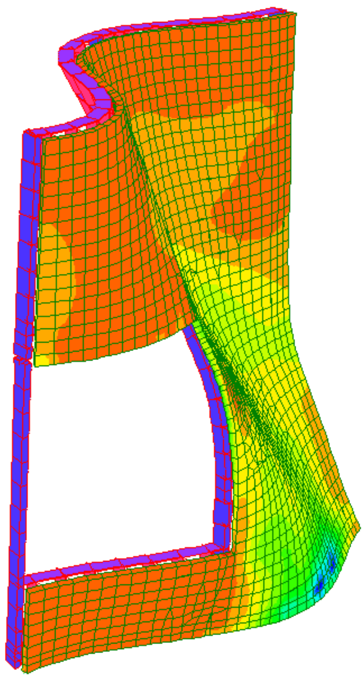

Figure 8: *Wall stress output for a typical brickwork panel*

The contour shows increased wall stress as the panel arches as a result of the brickwork geometry. Stress concentrations at the base of the panel are evident caused by the high lean. The magnitude of these stresses dictated the strengths required by the wall materials.

LABORATORY TESTING

The individual components and materials that make up the proposed design solution were tested to confirm their properties and behaviour.

A full sized mock panel was also constructed and tested to confirm the constructability of the system and validate the analysis.

Testing was carried out in conjunction with UTS Faculty of Engineering and Industrial Technology and Lend Lease's subcontractors.

5.1 MORTAR SELECTION

Mortar trials conducted early in the project did not demonstrate satisfactory flexural tensile strength based on the bond wrench procedure [5].That is, the bond between the mortar bed and brick was not sufficient. This was despite the use of very rich mixes (1 part cement: 0.25 parts lime: 3 parts sand) and the use of styrene butadiene latex as a 50% replacement of water.

Further mortar trials were carried out using different mix portions and admixtures. Each mix was tested for workability, compressive strength and flexural tensile strength. The aim was to achieve the following:

a) A characteristic flexural tensile strength of greater than 0.2MPa.

b) Elimination of lime and still achieve acceptable plasticity to reduce the risk of efflorescence.

c) Reduction of the sensitivity of mortar mix to quality variation due to material or environmental factors.

d) Quantification of mechanical properties for structural modelling.

A number of the tests carried out in this stage were also specified as part of the onsite quality assurance for the masonry façade.

5.2 WALL TIE TESTING

A series of tests were carried out to determine the behaviour and load capacity of the custom brick ties. The testing considered the composite action of the tie within the mortar bed in accordance with AS/NZS 2699.1 App B.

The test samples consisted of a brick tie within a mortar bed between two corbelled bricks as shown in Figure 9.

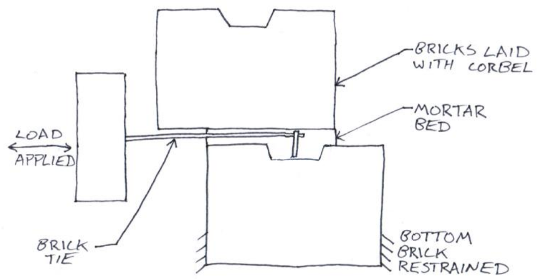

Figure 9: *Wall tie test arrangement*

A number of sets of samples were prepared to consider the worst case for a brick corbel in each direction and for the different tie types.

5.3 CONSTRUCTABILITY MOCK PANELS

Two full size mock panels were constructed to evaluate the constructability and structural performance of the design.

The setup consisted of a sloping-in panel and sloping-out panel, both reaching the maximum corbel on the building. The completed panels are shown in Figure 10.

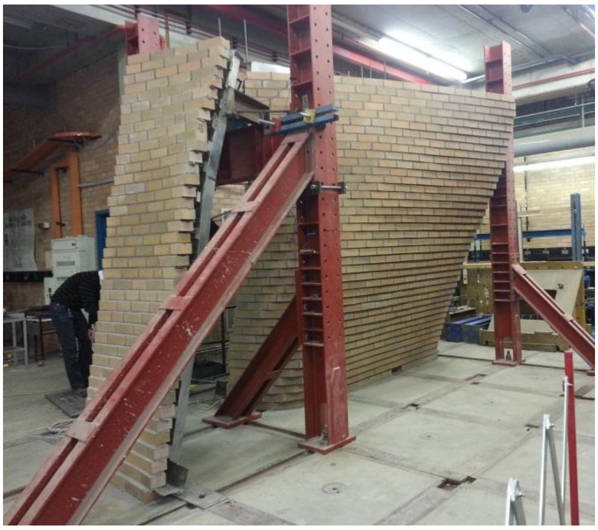

Figure 10: Completed mock-up panels. Leaning-in panel (Left) and leaning-out panel (right)

Strain gauges were installed to measure the load in the brick ties. This was used to validate the analysis models.

Once constructed, the panel was tested to failure using horizontal and vertical point loads. This was carried out at critical locations in order to demonstrate the performance under maintenance loads.

6 DESIGN OUTCOMES

6.1 MORTAR MIX

Following further mix trials, the final mix design had a sand:cement ratio of 1:4.5 and did not use lime.

A water reducer, viscosity modifier and integral curing agent were specified in the form of liquid admixtures.

The water reducing admixture was added to improve mechanical properties, the viscosity modifier to achieve the required workability and the integral curing admixture to help prevent rapid drying during construction.

Oven-dried sand was specified to enable better control of water content of the mix. The sand and cement was prepared in premixed bags to reduce the chance of error in mixing on-site.

The additives were also premixed in the water in an on-site reservoir to reduce variability between batches. This was trialled as part of a mix design testing process to ensure this process did not affect the mortar properties.

A small amount of black oxide was also added later to achieve the required architectural colour and tone.

6.2 BRICK-TIE SYSTEM

The performance of wall ties in regions of sloped brickwork is critical to the stability of the brick façade. The design and development of the brick tie system was one of the most important aspects of the brick façade design.

Research which encapsulated other non-traditional brick façade buildings was carried out to explore the possibility of integrating an existing structural system. Traditional or "off-the-shelf" wall ties were considered unsuitable for permanent high dead loads encountered on this façade. They generally did not provide the design capacities and performance characteristics that were required. A more robust system was developed to achieve a positive engagement and provide greater continuity to the façade wall.

The final design takes inspiration from traditional stone cladding support system as shown in Figure 11. In stone clad façades, the stones are supported individually using ties that lock into a groove concealed in the stone edge. Each stone is supported separately with minimal use of mortar. This connection creates a bearing effect to engage the stone with the tie when the cladding is subjected to out-of-plane loads.

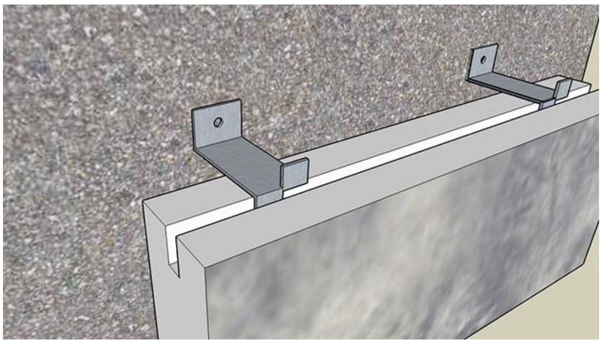

Figure 11: Typical stone cladding tie support system [7]

The final design is shown in Figure 12. It includes custom brick units, wall ties, mortar and bed reinforcement to achieve a positive bearing between the bricks and ties.

The proposed ties generally consist of a threaded rod with a square nut which is fixed to the steel substrate. The square nut is cast into the mortar bed in a continuous rebate in the top of the brick unit. This enables each tie to positively engage by end-bearing into the internal surfaces of the brick rebate.

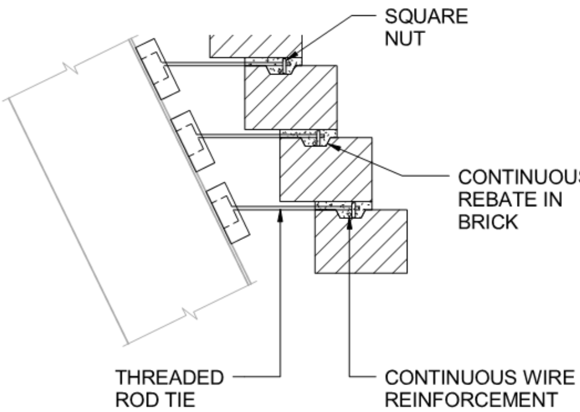

Figure 12: Custom Brick with rebate, tie and reinforcement

Although a brick with a traditional frog could achieve a similar engagement with the tie, the tie locations would have to be coordinated with the frog locations. The precision required to achieve this would be an unrealistic goal for the bricklaying tradesmen. By having a continuous rebate in the top of every brick, tolerances are built in with the position of ties meaning they can be located anywhere along the length of the course. This allows the ties to be prefabricated to the substrate in a factory prior to delivery to the site.

The brick rebate also houses a continuous horizontal reinforcing wire to distribute tie forces and control cracking.

Based on this general design philosophy for supporting the brick façade out-of-plane, the various components that make up the system were able to be developed to deal with all conditions on the project.

6.3 BRICK UNITS

A number of dry pressed brick shapes were developed each with a specific function on the building façade.

6.3.1 Standard brick with rebate

The majority of the façade is built using a standard 110mm wide brick with a continuous central rebate in the top centre of the unit. This typical shape facilitates the brick support system as described above for slight to moderate wall inclinations.

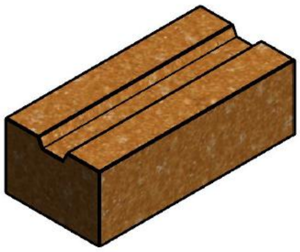

Figure 13: *Standard Brick with central rebate*

6.3.2 Standard with offset rebate

As noted above, in order to achieve engagement with the brick tie, the rebate must be contained within the mortar bed. This would not occur when the brick slope is most severe. Therefore, to accommodate these areas, a brick shape was produced that features a rebate that is offset from the centre of the brick. This could be used for both inward and outward corbel.

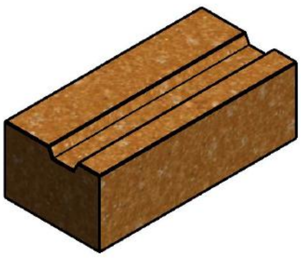

Figure 14: *Standard with offset rebate*

6.3.3 Standard without rebate

This brick shape is a simple solid brick of standard brick dimensions with no rebate. This is used at corners of the façade where the end of the brick will be visible.

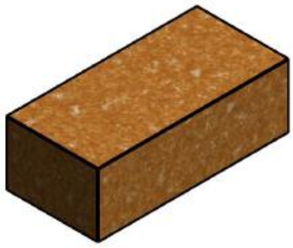

Figure 15: *Standard without rebate*

6.3.4 'L' brick (no rebate)

This 'L' shaped brick is used at the bottom course of panels and above window boxes to conceal the steel support plates. This brick does not need a rebate as wall ties are not required at these courses.

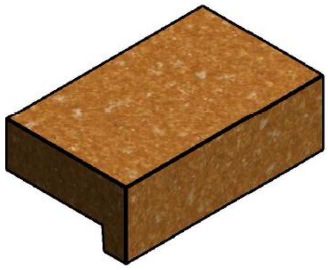

Figure 16: *'L' brick*

6.3.5 'K' brick with rebate

This brick protrudes from the curved wall surface by about 50mm on one edge. This brick was added by the architect in order to achieve the desired aesthetic effect.

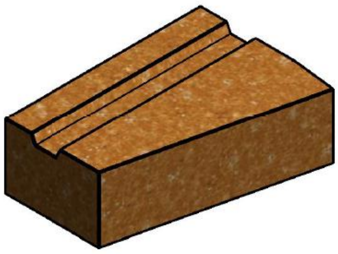

Figure 17: *'K' brick with rebate*

6.4 WALL TIES

6.4.1 Wall tie assembly

The wall tie assembly has a number of components to allow the tie to be fixed to the steel substrate and adjusted vertically to align with the mortar bed in a similar way to some proprietary tie systems. This system also allows the tie to rotate relative to the sloping substrate and project horizontally across the brick cavity.

6.4.2 Brick tie types

The tie assembly can house two tie types:

- Threaded rod tie as shown in Figure 18
- Flat bar tie as shown in Figure 19

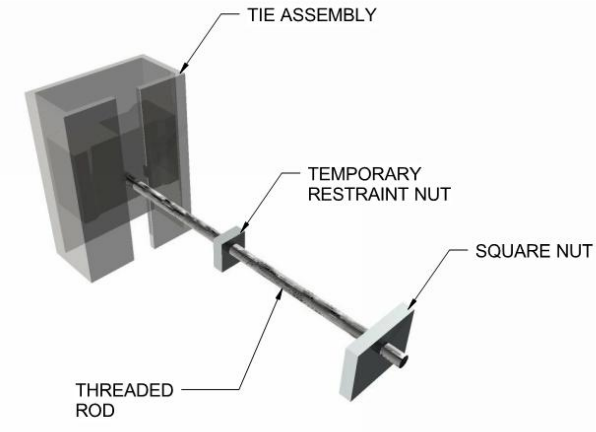

Figure 18: *Threaded rod tie type*

The use of a square nut engages mortar in the brick bed joint in a similar way to ties in stone cladding, as described in Section 6.2. This allows greater tensile and compressive capacities. This type of tie can be adjusted along the threaded rod to suit the location of the continuous brick rebate in the top of the brick. This tie can incorporate a temporary restraint nut which aids construction as described in Section 6.4.4.

This tie was used in panels that have complex and varying curvature due to its higher tolerance and ease of construction. This comprises approximately 35% of the building's brick façade area.

The flat bar tie consists of a simple steel bar with a 90 degree bend at its end to provide engagement.

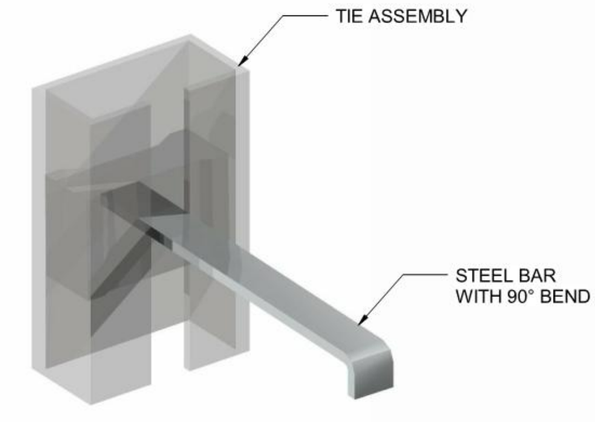

Figure 19: *Flat bar tie type*

This shape is simpler and more economic however it does not have the same levels of tolerance as the threaded rod tie. Consequently, this tie is appropriate for 'flatter' and only slightly corbelled areas of the brickwork façade. Approximately 65% of the brickwork façade is built using flat bar ties.

6.4.3 Brick tie layout

The primary factor that drove the brick tie layout was the need to eliminate tension in the brickwork under the dead load case. Although many aspects of this façade fall outside the realms of the Australian and International Standards, the requirement of 'AS3700 – Masonry Structures' was adopted as a primary element of the design philosophy. To achieve this, the ties must be spaced closer together vertically where the brick slope is greatest. In areas of maximum corbel (26 degrees), the ties are located at every course. Where the wall is near to vertical, the ties are spaced every 4th course. Typically, ties are located horizontally at every vertical steel stud of the substrate at 300 centres.

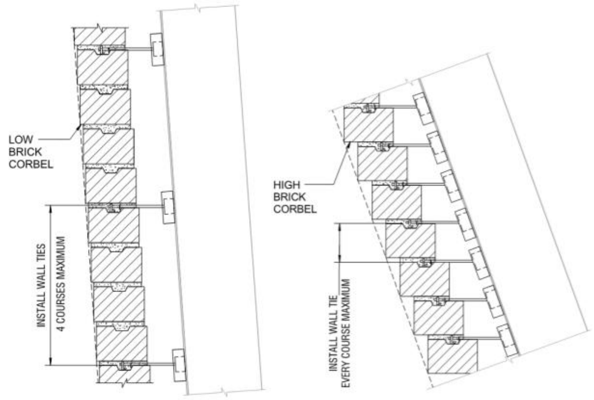

Figure 20: *Wall sections showing tie arrangement for a near vertical wall (left) and heavily corbelled wall (right)*

The tie spacing is specified to eliminate wall tension under dead load. As such, the brickwork can be built without temporary propping provided the ties give support during construction.

6.4.4 Temporary restraint

An off-the-shelf brick tie system was used for early mock panels which did not provide any significant temporary support of the bricks during construction. In areas of significant corbel, it was found that only a few brick courses could be laid at a time before the system became unstable and began to collapse. The brick layers were forced to wait until the mortar had begun to set before proceeding. This not only affected the efficiency of the bricklayers but also may compromise the mortar bond. This highlighted the requirement for a temporary restraint to the brickwork.

In order to address the issue of stability during construction, an additional component was added to the system in the form of a small square nut. This was put onto the threaded rod and adjusted such that it supported the brick itself before the mortar had hardened. Figure 21 shows the temporary support nut in an area of inward corbel. Note that for outward corbel, the nut is located on the inside of the brick rebate.

Figure 21: *Small temporary restraint nut supporting sloping in brickwork*

With this system, very little temporary propping was required to construct the brickwork even in areas of extreme brick slope.

7 CONCLUSIONS

Through the application of the latest design techniques we have pushed the boundaries of what can be achieved with masonry, one of the oldest building materials still in use.

The analysis, testing and design processes presented in this paper will have numerous applications on other difficult projects. The innovative structural system that has been developed can be adapted to other buildings with brittle cladding and complex geometries.

8 FUTURE RESEARCH

This paper is a broad case study of the analysis, design and testing of the masonry façade of the Dr Chau Chak Wing Building. There are a number of aspects that were summarised in this paper that can be explained and discussed in greater detail. The following publications are planned for future conferences:

- Finite Element Analysis of the Dr Chau Chak Wing Building Masonry Façade
- Mock Panel Testing of the Dr Chau Chak Wing Building Masonry Façade
- Mortar Selection and Testing of the Dr Chau Chak Wing Building Masonry Façade
- Construction of the Dr Chau Chak Wing Building Masonry Façade.

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