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SIMPLY COMPLEX

A case study of construction-driven design using computational methods

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Abstract. This paper explores how fabrication-based criteria can be integrated into design processes through computational methods. Based on the ongoing project of the Library of the Bao'an Cultural Complex in Shenzhen, China (referred as 'the Library' in this paper hereafter), this paper discusses the process of the rationalisation of an intuitive architectural form and its subsequent tiling design based on the adaptation to the conventional fabrication techniques of the building façade industry in China. These objectives are followed by the establishment of robust computational systems of automation that provide a concrete basis for the visualisation, the development of envelope details, and the generation of the list of component data for fabrication. This integrative approach is markedly different from a more conventional one, in which computational systems serve as a priori solutions to unconstraint design sketches.

Keywords. Fabrication criteria; rationalisation; computation workflow.

1. Background

At the competition stage, the architect had a vision of developing the architectural form of the three buildings, namely the Library, the Youth Palace and the Performance Centre, along the central green axis of Bao'an Central District, Shenzhen. Ruled surfaces defined as a surface formed by moving a straight line along a directrix curve (Pottmann et. al., 2007), each of which was formed by a straight line and a planar curve, were adopted as the form generator for all the three buildings. The Library discussed in this paper is the first building to be constructed.

2. Approach to the architectural geometry and envelope

The volume of the Library is defined by two curvilinear façades that bulge in and out along the north–south axis of the building, and an undulating open roof feature that splits in the middle to allow natural light penetration.

A double-façade system is adopted at the outset of the design development to isolate the shading screen from the glass envelope enclosure. This is a critical move that allows more freedom for the exploration of an open grid system for the fabric-like shading screen, which is less demanding in the developing of fabrication details compared to the inner enclosure system that calls for more sophisticated details to perform the function of waterproofing, thermal & acoustic insulation. The property of the design surface of the façade is therefore extremely critical for the design exploration and the subsequent fabrication of the outer open grid shading skin and the inner glass enclosure.

This paper focuses on the following three exercises that facilitate the tender drawing documentation and eventually the future fabrication:

1. Rationalisation of the design surface of the envelope;
2. Design exploration of the open grid shading screen configuration with respect to the design surface; and
3. Application of the planar glass panel onto the design surface and the subsequent development of curtain wall details.

The above exercises, together with the export of data through automation scripts that follows, produce the façade setting-out information for the entire curtain wall tender drawing package.

2.1. WORK FLOW

The workflow of the three aforesaid explorations can be summarised in the following flowchart (fig. 1). The input of fabrication criteria is based on the advice from the façade consultant and the discussion with façade fabrication.

3. Rationalisation of the design surface

3.1. ESTABLISHING CRITERIA: DESIGN SURFACE

In order to discretise curvilinear surfaces by means of façade components, i.e. by transferring a continual surface into discrete parts (Pottmann et. al., 2007), a design surface (Peters, 2007) is used as a basis for which anchoring points (or setting-out points) of these components are located. Therefore, in the case of the Smithsonian Courtyard Enclosure by Foster + Partners, where a rationalised freeform surface is used as a design surface for the populating enclosure components (Peters, 2007), the beams that support the shell are dis-

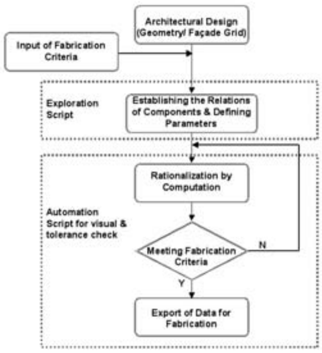

Figure 1. Workflow: criteria-to-computational systems

cretised as straight members aligned to the curvature of the design surface. That, and the setting out techniques required, may be deemed difficult for local contractors to follow.

From the point of fabrication, it would be much easier if all these setting-out points lie on the primary structure of the façade system, i.e., the mullions, and in terms of structural efficiency, it makes more sense if these structures are linear elements (the shortest span) that can be populated along the slab edge with equal spacing to ensure the span of the secondary components is well within an acceptable range.

3.2. OPTING FOR RULED SURFACES

It has been clear since the competition phase of the project that the team would opt for ruled surfaces as design surfaces for the facades and the roof. At that stage, however, no rules were established regarding the direction of the generatrices. This, as the team later discovered could be problematic for aligning straight mullions across the surface – either they would not be parallel with each other, in which case the glass units in the inner façade would become irregular quadrilateral infills, or, if parallel, equidistant curves are projected onto the surface and used as reference curves for mullions, the mullions would become segmented or curved members. Neither of the outcomes is pertinent to the design intent, nor are they economical for fabrication.

Therefore, the design surface needed to be fine-tuned: the generatrix, which rotates to form the bulges, is forced to be on a plane that is always perpendicular to the direction of the straight directrix (fig. 2). More specifically, in order to control how far the façade bulges out, the second directrix of the ruled surface is formed by connecting line-arc segments. Through controlling the chord length of the line-arc segments the bulging distance can be systematically controlled.

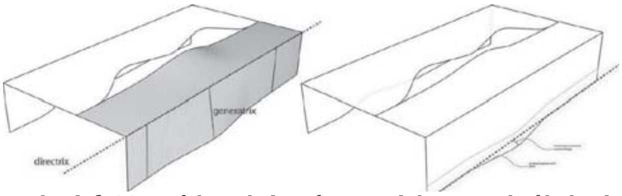

Figure 2. The definition of the ruled surfaces and the control of bulged surface.

The advantage of using ruled surfaces as design surfaces is that since the surface curves only in one direction, it is possible to align structural members (mullions in this case) along the direction of the straight generatrix, at a fixed spacing along the straight directrix. In addition, the distance between each façade component along a mullion can be obtained from simply dividing the length of the mullion into equal parts. In other words, a simple 2D grid, within which all points can be obtained through simple derivation, can be intuitively applied by the contractor.

4. Design exploration of the open grid shading screen

4.1. ESTABLISHING CRITERIA: LINEAR COMPONENTS

While the straight generatrices of the design surface are adopted as primary structural support, the shading fins, which run diagonally across the design surface, would either be curvilinear or segmented should they align with the design surface to form a weaving pattern. From the fabrication point of view, these segmented shading fins can take up different profiles to form a gradation pattern efficiently if all these profiles can be formed by folding the material instead of producing by extrusion through dies (fig. 3).

4.2. EXPLORATION SCRIPT FOR DESIGN EXPLORATION

This process of design investigations was facilitated by a series of 'Exploration Scripts' coded in Rhinoscript – a VBscript-based language used on Rhinoceros 4.0, a 3D NURBS modelling software. Exploiting its object-oriented properties the Exploration Scripts are built in a 'skeleton-modules' format.

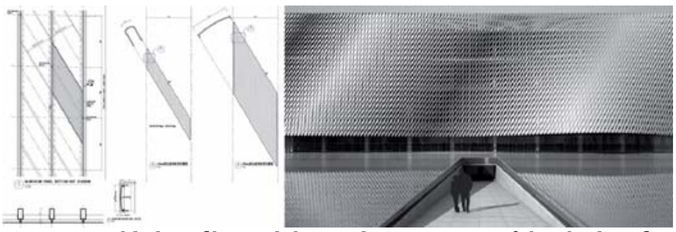

Figure 3. Folded profiles and the gradation pattern of the shading fins.

The structure of the exploration scripts look like this in pseudo-code form:

```
SKELETON{
    INPUT: design surface, top directrix, bottom directrix, generatrix
    VARIABLES: horizontal spacing between mullions, vertical
    spacing between facade components
    1. CREATE orthogonal grid
    2. TRANSLATE orthogonal into diagonal grid
    3. CALL mullion generation [to create mullions]
    4. CALL façade component generation [to populate diagonal fins
    between mullions]
}
END SKELETON
MODULE mullion generation
MODULE façade components generation
```

While the 'Skeleton' creates an orthogonal grid on the design surface and translates it into other grid systems (diagonal, hexagonal etc.), the 'modules' create the façade components at each node of the grid. The script was deliberately built flexible enough to visualise design decisions quickly. Furthermore, local parameters set for each module can be varied to create visual options for further design decisions (fig. 4 left).

It is worth-noting that with the 'skeleton-module' structure not only was the team able to visualise local parameters change quickly, but global parameters (such as the form of each façade component) as well. The 'mullion generation' module and the 'façade component generation' module, which generate diagonal fins between mullions, can be easily replaced with, say, a 'diagrid' module (fig. 4 right) using the same grid created in the 'Skeleton'.

4.3. DIGITAL MOCK-UP: FROM EXPLORATION SCRIPT TO AUTOMATION SCRIPT

Although the Automation Scripts are very similar to the Exploration Scripts in terms of their operations, the Automation Scripts are geared towards producing accurate digital mock-ups for construction cross checking and therefore need to be more robust in terms of parametric definitions. Like the

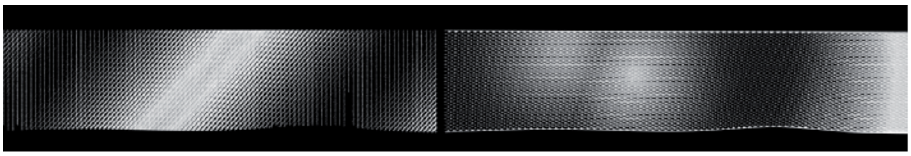

Figure 4. Design exploration of facade grid.

Exploration Scripts, the Automation Script partakes of a similar ‘skeleton-module’ structure:

```
SKELETON{
    INPUT: design surface, top directrix, bottom directrix, generatrix
    VARIABLES: horizontal spacing between mullions, vertical
    spacing between facade components
    CREATE orthogonal grid from horizontal and vertical spacing
    TRANSLATE orthogonal grid into diagonal grid
    CALL MODULE mullion generation [to create mullions]
    CALL façade components generation [to populate diagonal fins
    between mullions]
    CALL data export [to export components data for construction
    drawings]
}
END SKELETON
MODULE mullion generation
MODULE façade component generation
MODULE data export
```

The difference between the Exploration Scripts and the Automation Scripts can be best illustrated by the generation of gradation patterns on the façade. The gradation patterns are generated by varying the width of the fins along the same diagonal (dubbed ‘bands’) by a certain increment / decrement. In the Exploration Scripts, the increment / decrement Δ is expressed as:

Wmax : the maximum width of the fins, 500mm in this case
Wmin : the maximum width of the fins, 140mm in this case
Dmax : Distance between the maximum band and the setting out point
Dmin : Distance between the minimum band and the setting out point
S : the spacing between each mullion, which is 600mm in this case
Δ: increment width between adjacent bands
$\Delta = (Wmax - Wmin) / ((Dmax - Dmin) / S)$

While this simple formula alone can generate the gradation patterns needed for design explorations (e.g. moving Dmax and Dmin to different locations), the Δs at different points of the façade are almost bound to be irregular numbers. To eliminate these irregularities, Automation Scripts pin down the exact location of Dmax and Dmin (as multiples of S) and the increment (as either 10mm or 15mm).

5. Application of planar glass panel onto design surface

5.1. ESTABLISHING CRITERIA: PLANAR GLASS ON DESIGN SURFACE

The importance of maintaining a planar surface is crucial as curved double glazed unit would be extremely costly to produce in China. The adoption of a planar panel to tile up curved surface would mean at least one of the four vertices of a glass unit would pop out from the design surface. This would require special detailing in the mullion and transom design that can accommodate the variance of such vertex offset. Based on the functional requirement of the façade grid, the maximum offset is obtained through computation model and such data is adopted as the tolerance allowance in the mullion and transom design. It is worth mentioning that the planar glass panel is mounted on a non-planar frame. The deviations between the planar glass and the non-planar frame are to be covered by thermal break material on outside and aluminium covers on inside.

5.2. DIGITAL MOCK-UP AND AUTOMATION SCRIPT

A digital mock-up for the glass unit layout is used to visualise the deviation between the glass unit and the design surface (fig. 5), as well as to generate data that is exported as Geometry Method Statement.

The Automation Script in this case is written in Grasshopper, a plug-in for Rhinoceros that provides an interface for creating real-time parametric models. This Automation Script also exploits the object-oriented property of the language and therefore also partakes of a 'skeleton-module' structure:

```
SKELETON {
    INPUT: design surface
    VARIABLES: floor height, number of floors, mullion spacing
    1. CREATE sectional curves across the design surface at specified
    floor heights on planes that are parallel to the WorldXY Plane
```

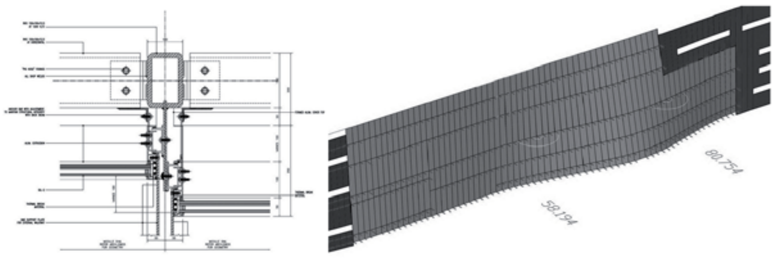

Figure 5. Deviation between glass unit and the design surface, and the corresponding mullion design to absorb the vertex offset.

```
    2. CONVERT sectional curves into connected segments at the
    specified mullion spacing
    3. CALL MODULE mullion generation [to create mullions]
    4. CALL glass unit generation
    5. CALL data export [to export deviation between glass surface and
    design surface for construction drawings]
}
END SKELETON

MODULE mullion generation
MODULE planar glass unit generation {
    INPUT: connected segments created from sectional curves
    VARIABLE:
    1. CREATE glass edge by connecting corresponding points on the
    connected segments
    2. CREATE, from the end points of a mullion (Pt A, Pt B) and the
    upper end point of the next mullion (Pt C), the plane on which the
    glass panel lies.
    3. PROJECT, along Y direction, the lower end point of the next
    mullion onto the plane on which the glass panel lies to create Pt D
    4. REGISTER the distance between the lower end point of the next
    mullion and Pt D. This would be the deviation (D) between the
    design surface and each planar glass surface.
    5. CREATE a planar surface using Pt A, Pt B, Pt C and Pt D as
    corner points. This planar surface would be the outer surface of a
    glass unit.
}
END MODULE
MODULE data export
```

6. Export of data for tender drawing documentation and fabrication

After crosschecking the design against the digital mock-up, it is crucial that the construction data, mostly issued as drawings to the local contractors, is accurately addressed in a format that is easy to follow. The team issued a set of Geometry Method Statement - a term used by Foster + Partners to describe “[a] set of rules and relationships that, if followed correctly, result in the determination of all the necessary set-out information for the project” (Peters, 2007). In the case of the Library, four sets of these Geometry Method Statements are issued to describe the setting out of all the components for the façade:

1. Mullion Setting (fig. 6): This set of data contains the ID number, angle of rotation along the straight directrix and length of each mullion. It establishes a

grid on the façade on which the façade contractors can identify every diagonal fin and derive its exact location with respect to the mullions.

2. Panel Matrix (fig. 7) This table allows the façade contractor to locate all diagonal fins on a façade and their respective widths. Since the location of Dmax, Dmin, and the increment width between adjacent bands, this table was used to govern the behavior of the automation script.
3. Plan Setting-out (fig. 6). This set of data, exported from the Automation Script allows the main contractor (responsible for the construction of the concrete slab) to locate points at which mullions are anchored to the concrete slab.

7. Conclusion

The case presented in this paper shows that for complex architectural surfaces, computation could serve as an instrument for integrating fabrication and setting out criteria into the design process such that these surfaces can be built from components fabricated and executed by facade contractors. In the case of the Library, computation is deemed useful in rationalising design surfaces into ruled surfaces with parallel generatrices on which façade components are populated. Doing so would allow mullions to be kept straight and undistorted as they conveniently follow the rotating generatrices. Upon

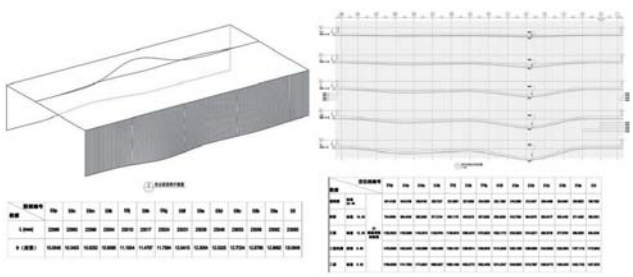

Figure 6. Mullion schedule and plan setting-out schedule.

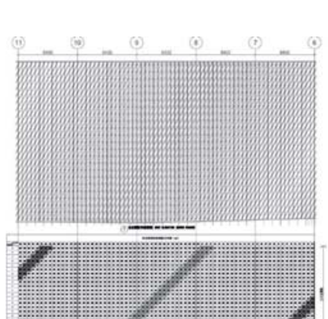

Figure 7. Shading fins with the corresponding width plotted on facade grid.

establishing fabrication criteria, well-structured computational tools can be used to generate design options quickly by either changing local variables, or changing global variables by replacing modules in a 'skeleton-module' script. Finally, automation scripts can be used to generate digital mock-ups for cross checking and exporting large quantity of fabrication and setting out data in batches for tender drawings.

Exporting data into a system of readable drawings is, in this case, a particularly important operation as it translates abstract geometrical intents into a system of readable drawings for contractors to follow. Given that construction drawings and diagrams are still the prevailing medium of communication among builders in China, this ability to translate would be the key to successful execution of construction.

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