A NOTATION TO AID COLUMN AND BEAM LAYOUT DESIGN FOR REINFORCED CONCRETE CONSTRUCTION IN CHINA

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Abstract. In this paper we report on the ongoing development of a toolkit to support the design of column and beam layouts for reinforced concrete structures in China. We present a visual, human- and machine-readable notation for architects and structural engineers to rapidly model column and beam layouts, as well as our underlying considerations. In conjunction with the toolkit, which consists of a CAD package, an editor, a parser, and an interpreter, the notation addresses aspects of local construction practice and supports design considerations including appearance, structural viability, constructability, and cost.

Keywords. Generative design; structural design; local materialisation; concrete; China; cost evaluation.

1. Introduction

Advances in digitally supported design encourage an understanding of architectural form as grounded in both geometry and mathematics (Burry and Burry, 2010). This understanding gives rise to digitally supported design approaches that not only lead to new shapes and forms, but also to the repositioning of form as performing structural functions (Moussavi, 2009), as well as to an increased interest in digitally supported design and fabrication methods (Oxman and Oxman, 2010; Yuan and Leach, 2013). While such approaches may be readily adopted in technically advanced construction cultures, they face challenges where they are imported to technologically developing construction cultures, such as those that are commonly encountered in China today.
Recent developments in generative design explorations address multiple criteria beyond the exploration of new forms through complex geometry, taking into account material performance and structure (Ahlquist and Menges, 2011). Such advances have yet to address constraints encountered in applied local construction. The work presented here takes a contrasting approach by aiding design that is based on tried-and-tested form languages with attention to local materialisation. Similar approaches have been described by Kamath (2013) and by HHD_FUN Architects (2013) who describe their strategy as "low technology parametric design".

The work presented here addresses the Chinese construction context, which makes extensive use of reinforced concrete (Herr and Fischer, 2013). Specifically, we are asking: How can column and beam structures be modelled, evaluated and modified rapidly to allow the cross-disciplinary negotiation of architectural design and engineering concerns in the context of Chinese concrete construction?

Our focus is on building types containing large spaces, such as schools, hospitals, shopping malls and office towers, which in China are characterised almost entirely by column and beam structures (figure 1). In this context we do not address residential Chinese construction, which differs from non-residential construction by making extensive use of load-bearing walls, and by shorter ceiling spans that require considerably less secondary beam support.

Column and beam based concrete construction in China differs from concrete construction in Western contexts due to differences in a range of local conditions – in particular labour skills and cost, material quality and cost, as well as construction scale and speed. In the West, relatively expensive labour costs and relatively cheap, high quality materials typically lead to flat floor slabs with two-way reinforcement (rebar integrated in two mutually orthogonal directions). Construction in contemporary China is based on processes that can be performed by unskilled (typically migrant) workers. The resulting low labour costs and relatively expensive materials with mixed qualities lead to the labour-intensive in-situ casting of primary and secondary reinforced concrete beam structures underneath thin floor slabs with one-way reinforcement (unidirectional rebar). Other differences result from China’s population size and density as well as from the country’s speed of development and urbanisation. Scales of Chinese construction projects tend to dwarf construction scales elsewhere, while design and construction work in China typically face the pressure of extremely short deadlines.

These local conditions result in an invariable approach to concrete-based structural design, which readily lends itself to formal representation by minimal symbolic and syntactic means. The work presented here aims to exploit
this circumstance to offer multiple benefits, including improved interaction between architectural and structural design, improved quality of interior spaces, ensured structural viability and constructability, and cost control.

2. The typical design process of concrete frame structures in China

Building projects in China typically rely on fast design specification in a one-directional workflow, which disassociates the roles of architects and structural engineers (Fischer, 2012). In this workflow, architects design floor plans in predominantly regular grids, which determine column placements at grid intervals. These column grids in turn determine the layouts of primary ceiling support beams. As parts of finalised architectural design specifications, these floor plans are then passed on to structural engineers, who ensure structural soundness essentially by dimensioning columns and beams, as well as by placing secondary beams. This stage is characterised by numerical rigour in the dimensioning of structural elements, by the application of rules of thumb regarding the constructability of formwork, and usually by little aesthetic sensitivity. The linear determination that connects beam layouts to the placement of columns and further down to the grid lattices that underlie floor plans is somewhat analogous to geometric continuity in Gothic architecture, where, in the ideal case, the shapes and placements of columns bases determine the shape and structure of vaults (Gilman, 1920, p. 44). While it can be assumed that possibilities and constraints of vault structures have informed Gothic column placements, there is currently virtually no such two-way determination in the Chinese concrete construction design workflow. Consultations between structural engineers and architects are uncommon and beam layouts are virtually never reviewed by architectural designers. Resulting in lacunar ceilings, they have the potential to affect the quality of interior spaces for better or for worse – especially where columns are placed irregularly (see Herr and Fischer, 2013, fig. 2). The potential of such structures to enhance architectural quality besides offering load-bearing capacities, however, is currently under-recognised amongst Chinese architects (ibid.). Reinforced concrete structures throughout China have mixed visual appeal, and by default are hidden behind claddings and above suspended ceilings. This practice contributes to a widespread lack of awareness of structural notions and of the tectonic qualities that structures can contribute to architectural expression, even among architectural professionals.

3. Appearance, structural viability, constructability, cost and layout

Investigating the potential of generatively supported column and beam layout design for concrete construction in China (Herr and Fischer, 2013), we
previously identified four key aspects that a generative parametric approach to structural layout design should address: appearance, structural viability, constructability, and cost. In principle, each of these four aspects has the potential to enhance, to inform, or to work against any of the other three. Visual appeal, for example, is not necessarily a good indicator of structural viability, and vice versa. As previously discussed, while visually appealing, Delaunay and Voronoi lattices as potential beam layouts are less structurally viable than other, more conventional lattice types (ibid.). Cost minimisation by way of material reduction may impact visual appeal either positively or negatively, and vice versa. And so on. This interdependence of multiple criteria opens up a space for context-specific and design considerations.

Neither column layout, nor considerations of appearance, of structural viability, of constructability, or of cost are exclusive to the purview of either architect or structural engineer. Therefore, the currently dominant linear workflow between disassociated architectural design and structural design stages is not conducive to context-specific and creative considerations. The current workflow simply minimises cost and time required for both design and construction, based on tried-and-tested solutions to ensure constructability and structural viability, while ignoring (and covering up) effects on appearance. Improving this approach by digital means is challenging, not only because it virtually defines an entire construction industry, but also because more design considerations are likely to introduce added cost and a need for more time.

4. Toolmaking considerations

For these reasons, besides addressing appearance, structural viability, constructability, and cost, a digital toolkit to support the design of column and beam layouts must also enable interaction between architectural designers and structural designers, while allowing for the rapid generation, exploration, modification, and evaluation of alternative options (see figure 2).

Explorations in the multi-criteria design space outlined above, and the relative weighting of layout, aesthetic, structural, construction, and cost considerations should not be subject to automated decision making, but to negotiated decision making between architects and engineers. In this sense, the aim of the design support toolkit is not to limit design options for architects by way of automated optimisation, but to support designers in the exploration, evaluation, and specification of structural layouts. During this process, designers should be informed about structural and cost implications of proposed column and beam layouts to support sensible decision making without undue limiting of design choices.
To enable such joint explorations and decision making, the interaction between architectural and structural designers should occur in joint sessions supported by a tool that is available on a single shared computer and operated by one person at a time. Simultaneous multi-workstation remote access to a shared data set is technically possible, but not a priority in our investigation because remote collaboration would quite possibly work against the desired thorough engagement of members of both professions.

The approach presented here stays within the general form language, constraints, and practices that define current column and beam construction in China. It does not challenge current strategies to ensure structural viability and constructability. Instead, it takes advantage of the straightforwardness of these strategies, which allow highly efficient representations of concrete and beam structures as graph data structures. We are proposing a minimal notation and a toolkit for this purpose. They are described in greater detail below.

Adhering to current strategies, the assurance of structural viability can proceed by checking dimensions of structural elements against tried-and-tested rules-of-thumb. This applies chiefly to the spans of beams, which, in the case of primary beams, depend on the placement and spacing of columns. The placement and spacing of beams must be related to the layout of building floor plans. This is where structural layout and functional layout meet. Ideally, this layout coordination should be supported with suitable two-dimensional and three-dimensional visual representations, which can also aid the evaluation of the appearance of proposed structures.

Grid-based column layouts result in highly periodic tessellations of beam patterns can efficiently be specified as abstract units, which we call "tiles". Chinese concrete frame structures feature primary beams with spans of up to 12 meters, and relatively dense grids of secondary beams with spans of up to 7 meters. Secondary beams are constrained less by their length than their
spacing (up to 4 meters) to support thin one-way spanning floor slabs. Primary beam spans exceeding lengths of 12 meters are uncommon because their required structural height likely limits the usability of spaces underneath. Secondary beams should connect to primary beams as directly as possible, and maintain continuity with other secondary beams to reduce bending moments and excessive deflections. This can be ensured easily by visual inspection of suitable visualisations.

Beams generally meet at one of two types of locations (which we refer to as nodes): supported (i.e. at a column) or unsupported (cantilevered). Both must be supported by the toolkit. Connections of more than six beams meeting at one node are difficult to construct and should generally be avoided, unless a drop panel is introduced around the column top. Beams meeting at excessively sharp angles should furthermore be avoided since sharp-angled joints are difficult to construct. Both the number of beams meeting at a node and the angles between meeting columns can and should be checked computationally. Ensuring constructability, of course, involves the generation of construction drawings, which hence must be supported by a toolkit for the purposes described here.

In the Chinese context, cost of reinforced concrete structures is calculated as a positive function of a given structure’s volume (the rate is around RMB1,800 per m$^3$). This is due both to the restricted approach to concrete construction, which results in large numbers of, and a relatively constant ratio between, the number of columns, beams and floor slabs, irrespectively of building type, building height, and floor area, and to relatively high material costs and relatively low labour costs. A design support toolkit capable of generating construction drawings necessarily has access to all parameters required to calculate total column and beam volume, and thus, in this context, to project cost.

5. A toolkit to design concrete column and beam layouts

The toolkit we are developing uses Rhino3D as a visual editing frontend as well as for the production of drawings. Our current use of Rhino3D is motivated by our familiarity with using and programming this package. Ideally, it should be reconsidered in favour of AutoCAD, which is more widely used in architectural and engineering practices in China. Besides Rhino3D we use an MS Excel based VBA program and GUI as an editing frontend to specify various input data such as rectangular or round column dimensions; to place nodes within floor plans, either individually or automatically in grids; to move or remove columns; to place beams, and so on (figure 3).
Editing occurs in either the VBA program or in Rhino and results in an abstract representation of column and beam layouts for which we have developed a purpose-oriented notation (see the following section).

Based on associative geometry, the toolkit allows iterative cycles of adding, modifying, and removing columns, beams, and tiles by adding, modifying and removing corresponding notational elements, which are visualised in Rhino3D, ideally superimposed on a locked layer showing intended floor plans. These topological modifications of what are effectively parametric schemas can prevent undesirable parametric design restrictions that are due to fixed schemas (Herr, 2011). The editing process requires the frequent parsing of a given notational specification and the maintenance of a corresponding graph structure, which is held as Excel spreadsheet data.

6. A notation to represent column and beam layouts

Derived from regular grids, the concrete structures we are concerned with here are more often than not characterised by a large degree of repetition both in the horizontal plane and the vertical plane. Such redundancy allows for efficient encoding by way of scripting in a suitably specified procedural language. Script-based representations for structural configurations, however, lack the spatiality and visual accessibility necessary for architectural designers to relate column and beam layouts representations to floor plans. In CAD-based drawing, on the other hand, the approach commonly taken to de-
fine and communicate column and beam layouts, is inherently spatial and allows superimposition onto plan drawings, but it is relatively slow and does not allow easy modifications and explorations of alternatives.

For these reasons, we have devised a human- and machine-readable visual notation that can be manipulated rapidly, superimposed on floor plans, and interpreted as a column and beam layout. The notation contains elements for all required data that relates to plan locations: nodes, beams, and tiles. Besides quadrilateral tiles it also supports triangular tiles, which are specified in a rotation-sensitive manner (table 1).

Table 1. Types and formats of toolkit inputs (including notational elements) and outputs.

<table>
<thead>
<tr>
<th>INPUT</th>
<th>OUTPUT</th>
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<tbody>
<tr>
<td>Type</td>
<td>Format</td>
</tr>
<tr>
<td>node locations</td>
<td>set of beam widths and depths</td>
</tr>
<tr>
<td>• supported (column)</td>
<td>Rhino3D rectangle</td>
</tr>
<tr>
<td>• unsupported (cantilever)</td>
<td>Rhino3D circle</td>
</tr>
<tr>
<td>column dimensions</td>
<td>numerical data</td>
</tr>
<tr>
<td>beams</td>
<td>straight note-to-node Rhino3D line</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>tile locations</td>
<td>construction drawings showing outlines of columns, primary and secondary beams and drop plates</td>
</tr>
<tr>
<td>• 3 nodes (trilateral)</td>
<td>3D visualisations</td>
</tr>
<tr>
<td>• 4 nodes (quadrilateral)</td>
<td>Rhino3D drawings placing primary and secondary beams relatively to 3 or 4 nodes</td>
</tr>
<tr>
<td>tile patterns</td>
<td>example output (illustration)</td>
</tr>
<tr>
<td>• 3 nodes (trilateral)</td>
<td>example input (illustration)</td>
</tr>
<tr>
<td>• 4 nodes (quadrilateral)</td>
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</table>

Primary and secondary beam dimensions, as well as drop panels and drop panel dimensions, do not need to be specified as inputs, but are provided by the system as outputs. Figure 4 shows a typical floor plan, the abstract representation of a structural grid layout using the described human- and machine-readable notation, and a derived column and beam layout drawing.
Figure 4. Floor plan of an existing building (top), specification of column and beam layout using the described notation (middle) and derived column and beam layout (bottom).
7. Current status and outlook

We reported on the ongoing development of a toolkit to support architectural and structural designers in the joint design of column and beam layouts for reinforced concrete frame structures in China. The toolkit takes into account constraints of local construction practice and supports design decision-making with regards to appearance, structural viability, constructability, cost and layout. It allows the rapid specification and evaluation of structurally sensible column and beam layouts. We have developed a editor for this notation as well as a parser suitable to derive and maintain corresponding graph data structures. Future work will include the integration of a suitable interpreter to derive column and beam layout drawings from the graph data structure.

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References