DEVELOPMENT OF AN INTELLIGENT 3D PARAMETRIC MODELING SYSTEM FOR THE NORTH AMERICAN PRECAST CONCRETE INDUSTRY: PHASE II

Ghang Lee[1], Rafael Sacks [2] Charles Eastman[1], and Ragnar Wessman[3]

[1]College of Architecture, Georgia Institute of Technology, USA

[2]Civil and Environmental Engineering, Technion, Israel Institute of Technology, Israel

[3]Tekla Corporation, Finland

ghang.lee@arch.gatech.edu

Abstract: 3D parametric modeling technology was first introduced about 15 years ago, but still only a few sectors in Architecture, Engineering, and Construction (AEC) have successfully adopted the technology in production. This paper reports the second phase of an early successful collaboration project between an industry sector, academia and a CAD vendor to develop an intelligent 3D parametric CAD system for the precast concrete industry in North America.

Keywords: parametric modeling, intelligent CAD, precast and prestressed concrete

1. INTRODUCTION

Automation of design and detailing in construction with intelligent 3D modeling instead of 2D drafting is beneficial in enhancing engineering and production productivity [1]. The Precast Concrete Software Consortium (PCSC) has pioneered development of an advanced 3D precast concrete building modeling system. The PCSC consists of major precast concrete producers in Canada and the US. The goals are to fully automate and integrate engineering, production, and construction operations, to gain productivity, and ultimately to increase market share. The first three authors are the technical advisory team to the PCSC, led by Charles Eastman at Georgia Tech.

The first phase of the PCSC project began in 2001 with a study of precast concrete processes, critical process cases, and the definition of a request for proposal to develop a precast concrete design and production software system based on parametric modeling. An 88-page request for proposal (RFP) with the business and technical requirements [2] was generated and distributed to major CAD vendors. The vendors included Autodesk, Bentley, Nemetschek, DiCAD, EDS-PLM (Unigraphics), Solidworks, and Tekla. After an eight month review of 12 proposals, the proposals were shortlisted to five, then two finalists. Tekla, with a strong 3D parametric CAD engine and the engineering and detailing capabilities for AEC, was selected as the precast CAD platform developer. The second phase began in April, 2003. More than 30 detailed technical requirements specifications were developed collaboratively by the PCSC, Tekla, and the Georgia Tech - Technion team.

The progress and findings from the first phase of the PCSC project have been reported and discussed in several places from various perspectives [2-9]. This paper reports the progress made in the second phase of the PCSC project, in which the PCSC members, the Georgia Tech - Technion team, and Tekla, have collaboratively organized and specified precast-concrete-specific functions that are required to automate design and detailing of precast concrete pieces. This paper describes the technical requirements for transforming generic parametric modeling functions into practical solutions used for the North American precast concrete industry. As of June 1, three beta versions of the advanced precast concrete CAD system have been released based on the technical specifications. Member companies have ghosted real projects using the beta versions. Results from pilot projects indicate that *engineering productivity* can be more than doubled [10]. This paper also briefly reports the results of pilot projects.

2. DETAILED TECHNICAL REQUIREMENTS SPECIFICATION

In order to automate design and detailing, a system must be *intelligent*. By *intelligence*, we mean "the ability (of a CAD system) to "maintain semantic integrity. The system helps keeping the representation of the evolving design consistent with its meaning " [4]. However, the *intelligence* of a CAD system comes from domain expertise, not from within a system itself.

The first challenge we faced in the development of an intelligent CAD system was to collect and develop detailed technical specifications from domain experts.

It was also necessary to prioritize the required functionality, as project scope did not allow implementation of all the functions that were desired by the members. The priorities of development items were set by a matrix of the following three considerations:

- *Development effort*: how much effort is required to develop the function (in terms of work hours)?
- *Commonality/criticality*: how common or critical is the function in producing real precast concrete projects?
- *Effectiveness:* As a conclusion, how beneficial is a function in productivity gain and error reduction?

The significance of each criterion is relative. Many software functions may be important in modeling and automating real projects. The importance of functions must also be balanced with development costs. Some functions may take much longer to develop than others. However, any function that is essential for accomplishing a project must take priority over other development items that may enhance productivity, but can be 'worked around.' *Warping* is an example of an essential function. (See Section 2.2 for more information on warping).

Based on the above three criteria, preliminary development items were selected and specified in the *preliminary development item outline specification* as part of the official contract between the PCSC and Tekla. The arrangement was that the PCSC's technical committee would help Tekla to collaboratively generate detailed functional/technical specifications based on the earlier preliminary development specification [7] by providing needed precast domain expertise. In return, the PCSC companies were offered a significant discount and service as favored customers.

The preliminary development items were grouped in the following eight task groups for detailed specification:

1) Piece Modeling and Numbering
2) Connections & Joints
3) Surface Treatments
4) Building Assemblies
5) Drawings and Reports
6) Embeds
7) General Modeling
8) System Functions

A major challenge for collaboration in the development of the specifications was the geographic dispersion of the participants. Offices of the PCSC member companies, the Georgia Tech and Technion team, and Tekla were dispersed over 15 different locations across four countries (Canada, the US, Finland, and Israel). Various communication methods, e.g., weekly teleconferences, bi-monthly 3-day meetings, and a highly interactive custom-made website, were deployed to facilitate the collaboration across continents. The website included discussion forums, repositories for reference materials (drawings, reports), and e-mail distribution and other functions. In all, 397 MB, (1,655 files) of drawings, documents, reports, tables, and figures were collected and compiled through 447 distinct discussion threads. The website has been developed and maintained by the Georgia Tech team since the PCSC project's inception. The website was enhanced and customized as the interim goals of the consortium changed through each phase of the project. There were several mechanisms to promote collaboration on the project website: a history log, hit counters for each posting, search functions, various view options, a 3D model webviewer adapted from Tekla's Webviewer, and more. The PCSC project website can be found at http://dcom.arch.gatech.edu/pci.

Currently, as the role of the consortium is being transformed to that of a user group, several parts of the PCSC website are slowly migrating to Tekla's new user-forum website.

The following sections introduce the major precast-specific domain expertise and required system functions specified through the collaboration between PCSC, the Georgia & Technion team, and Tekla.

2.1 Parametric Piece Definitions

A major advantage of parametric modeling is its ability to embed intelligent object behavior without complex programming. However, if every building object and its behavior needed to be designed and implemented by users, the effort would be very time-consuming and error-prone.

It becomes very difficult to implement certain intelligent behavior in a system without pre-defining domain-specific objects. For example, if we want to develop a function to automatically design a connection between two precast concrete pieces (e.g., a connection between a *beam* and a *column*), a system should be able to distinguish a primary member and secondary member. Core precast concrete objects should be predefined at an abstract level. We call them *Abstract Function Objects (AFOs)* [3]. Later, users can develop their own custom pieces (such as column and beam) as an instance of an AFO to designate primary and secondary objects.

Major precast concrete products, which were defined through the requirements specification phase, include double tees, spandrels, hollowcore, beams, foundations, columns, walls, and stairs. Drawings and examples of each product type were collected and categorized. Their parametric definitions have been specified.

2.2 Special Piece Modeling Functions

There are generic modeling functions that are required by most products whereas there are industry-specific “shape transformation” functions that can greatly reduce users’ efforts and time to model certain types of products. Many precast concrete products require shape transformation functions because their shape in production is not the same as their shape in situ. All prestressed pieces experience elastic shortening once they are stripped from their forms. Some also have a camber (vertical plane curvature along their axis) if the prestressing is eccentric. In addition to these two transformations, double-tee floor pieces are also often intentionally warped along their length in order to create slope for drainage (Figure 1).

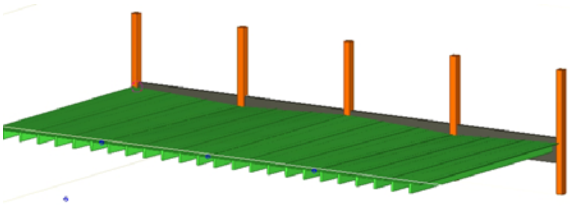

Figure 1. Warping of Precast Concrete Slabs (Note the depression of the slab at the second and fourth columns).

If these shape transformations are not properly considered in the design, engineering, and production phases, the produced pieces will not fit correctly: they could also be too short, too long, or too curved. when they are delivered to a construction site. Currently, these shape transformations have to be calculated by hand. But with the 3D geometric definition of a precast concrete piece, this is one of the engineering calculations that can be easily and efficiently done by the system.

2.3 Piece Numbering Schemes

Precast concrete pieces are managed and controlled by different identifiers at different lifecycle phases. In the schematic design phase, a precast concrete piece is controlled by its product type (e.g., column, double-tee, slab). The control number at this phase is called a *product code*. In engineering and detailing, a precast concrete piece gains specific geometry. All precast concrete pieces with “similar” geometry are regarded as the same piece for production. The control number for similar pieces is called a *piece mark* in the North American precast concrete industry. Similar pieces are usually identified by the overall shapes of precast concrete pieces. But each company has slightly different identification rules depending on its production methods or practice. Subtle differences (or variations) between similar pieces are denoted by qualifiers added to the end of pieces marks. A third numbering is the *production serial number*, which is unique for each piece of concrete produced. Scheduling of precast concrete piece production is a complex optimization process considering the erection schedule and production capacity utilization. Naturally, the production serial number (or piece mark) of a piece is different from the *erection sequence number* and the *inventory (location) number*, which depicts the location of a piece on a storage yard. Design, production, finishing, storage, shipping, erection, and management of them, are all areas that require deep understanding of precast concrete practices and optimization processes.

2.4 Connections

Another example of an intelligent precast design / engineering function we specified is parametric connections. In order to increase the productivity of precast concrete piece design and engineering, automation of connection design was considered essential. Parametric modeling systems should apply connections parametrically and maintain the geometric integrity of precast pieces in assemblies, and of the connections between them, by embedding the required behavior of pieces and connections in response to design or detailing changes. For example, application of a column to column splice should include generation of parametric parts as shown in Table 1.

However, providing thorough definitions of how precast pieces and connections should respond was a key challenge, because of the difficulty in describing dynamic effects in an unambiguous way using static drawings. As a shorthand for describing Building Object Behavior (BOB), the Georgia Tech team developed a notation, called the *BOB notation*. The BOB model for parametric connection design includes fields such as *connection name, version, author, data, primary (supporting) part, multiple secondary (supported) parts, planned use, known limitations/rules*, and *definitions & default values of parameters*.

There is no such thing as a generic connection between two parts. Only certain types of connections can be used depending on the geometric shapes and load conditions of connected parts. For example, the column-to-column splice with anchor bolts (C-C-AB) connection illustrated in Figure 2 can be used only between a rectangular column and rectangular column or between a rectangular column and a rectangular Cast-In-Place (CIP) footing.

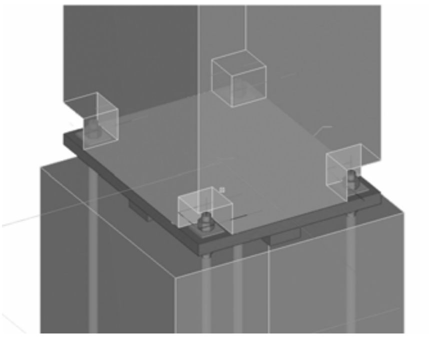

Figure 2 A column-to-column splice with anchor bolts connection (C-C-AB)

Table 1 Planned use and known limitations of a connection

Planned Use (Initial Goals for Functionality):
• Create a fitting between columns (Adjustable Grout Joint) • Create Base Plate (Adjustable Thickness, associative size with column & associative hole diameter with Base Plate) • Create 4 Shim packs (Adjustable size & offset from column face) • Create 4 Anchor Bolts (Adjustable size/projection/embedment and offset from column face) • Create Nuts & Washers (Adjustable sizes with associative hole diameters to Anchor Bolts) • Create Pockets (Associative to column face, adjustable offset to T/O Anchor Bolt and AB offset from Column face) • Create Grout Bed (to track volume)

Known Limitations/Rules:
• Can only be used with square or rect. columns. (no rounded surfaces) • Main / Secondary column faces should be parallel (non-aligned columns must be visually checked & adjusted to suit) • Can only be used with square or rect. columns. (no rounded surfaces) • Main / Secondary column faces should be parallel (non-aligned columns must be visually checked & adjusted to suit) • Bottom (Main) object must be equal to or larger than Top (Secondary) object • Base plate cannot be created wider than column

A large set of basic precast connections was collected along with examples of them. Most of these were implemented as parametric connections by technical committee members and shared using the website. Some of the basic connections modeled include:

- Double Tee to Flange Connection
- Double Tee to Cast-In-Place Ramp Connection
- Spandrel/Wall Continuous Footing Connection
- Spandrel to Steel Column Tie Back Connection
- Double Tee Solid Wall Connection
- Inverted Tee to Column Connection
- Spandrel Column (load bearing) Connection

In practice, the parametric object planner and the BOB notation were employed only in some cases through the requirements specification phase and the parametric connection implementation phase. We identified several limitations. There was no mechanism and application to directly transform the specified building object behavior in the notation into real parametric object. Therefore, as users became more proficient at implementing and editing parametric connections directly in the software, full specification of building object behavior became a cumbersome and additional task. However, the need for explicit descriptions of expected/implemented building object behaviors was underlined by copious e-mail communication between PCSC members in the process of sharing developed parametric objects among them. Parametric objects without good descriptions of the intended behaviors are like computer-implemented functions without good documentation. As parametric modeling tools become more prevalent, an efficient method to explicitly and unambiguously describe the design intentions will be crucial.

2.5 Building Assemblies

Some building components can be controlled much more efficiently as an assembly than as an individual piece. For example, a stairwell and an elevator shaft often pierce through several stories. If the location of a stairwell changes, the holes, which penetrate through several floors should be moved together and the locations of attached connections should be adjusted.

In precast, the act of dividing the façade of a building into a production-optimized, yet aesthetically pleasing, shape is called *panelization*. Each façade piece will be manufactured individually. However, in the design phase, users should be able to edit the façade as a whole if they wish. Later, joints and connections can be added along the panelization grids in order to divide a façade into individual pieces.

These are only a small number of examples of building assemblies. Another example includes a floor assembly, washes, and toppings.

2.6 Drawings and Reports

Drawings are often accused of being an ambiguous form of representation, but are indeed a succinct

summary of complex geometry. They are an effective communication medium between different parties for some tasks. Drawings cannot be fully automatically generated by a system because each company has different conventions for abstracting and simplifying certain things and also because each project has its own dimensioning requirements.
Automated report generation (e.g., bill of materials) is another complex issue. Each company has different ways of calculating surface areas and volumes of pieces depending on product types and other detailed estimation rules: e.g., whether to ignore or count small holes and reveals.
The PCSC members collected hundreds of drawings and reports and analyzed required representation types and data fields for the precast concrete industry through the detailed specification process.

2.7 Automated Rebar Design and Embeds

There are three major building codes (i.e., IBC, BOCA, and UBC) used in the US, as well as regional building codes. Canada has its own building code and also many regional codes. The US uses the imperial measurement and Canada uses the metric system. Thus, standard rebar, strands and meshes are different, and the details are different. Various examples and standards were collected and categorized through the specification process.

2.8 Other Functions

The items and details listed in this paper are only the tip of the iceberg. The technical specification developed covers short-term issues such as user-interface improvement issues and long-term development issues such as the Precast Concrete Product Model (PCPM) implementation for data exchange between different applications.

3. PROJECT GHOSTING

Three beta versions of a new product, named *Tekla Structures*®, have been developed and released for the PCSC members to review. The PCSC member companies "ghosted" (i.e. reproduced) real projects using the beta versions in parallel to the production of precast concrete using traditional 2D drafting systems. The purpose was to identify functionality gaps possibly missed in the specification process. Figure 3 illustrates an example of a parking garage modeled by David Mahaffy at Strescon Ltd.

Figure 3 Queen Elizabeth II Health Sciences Center Parkade, Halifax, Nova Scotia

Initial improvements in engineering productivity have been assessed. Modeling of full building structures, including their connections, and producing general arrangement drawings, could be accomplished in less than half the time using the prototype 3D CAD system than could be achieved when using traditional 2D drafting systems. Table 2 shows the work rates by project size. Table 3 shows how the project sizes were defined. Detailed information on the results is available in [1]. Note that this does not include rebar detailing and other functions, which have not been delivered yet.

Table 2 Comparison of Engineering Productivity

Project Size	2D Drafting (hours per 1,000m^2)	3D CAD (hours per 1,000m^2)
Medium	52.5 hours	2.3 - 5.9 hours
Small	171.5 hours	5.7 hours

Table 3 The Project Sizes

Project Type	Size Measure	Small	Medium
Architectural	Façade area (m^2)	≤ 1,000	1,001–10,000
	Piece Count	≤ 100	101–750
Structural	Floor area (m^2)	≤ 7,500	7,501– 30,000
	Piece Count	≤ 250	251–1,000

4. DISCUSSION

There have been many past efforts to automate certain aspects of precast concrete design, engineering, and production. But the PCSC project is the first industry-wide attempt to develop an integrated design and engineering 3D CAD system for the North American precast concrete industry. The PCSC project involves a unique collaboration between an industry sector (i.e., the precast concrete sector), academia, and a major CAD vendor specializing in Architecture, Engineering, and

Construction (AEC). The key success factors can be summarized as follows [8]:

- effective leadership within the precast industry,
- careful planning with proactive teams,
- project coordinators/facilitators that can lead the direction and the scope of the project towards realizable goals (e.g., Georgia Tech)
- fear of progress made by competing sectors (e.g., the steel construction sector)
- clear and reliable economic impact assessment [9-11]
- early initial consensus regarding the potential of 3D modeling replacing 2D drafting
- identification of a suitable 3D parametric platform

Some may argue that the success of this project may be due to the fact that the precast concrete sector is more manufacturing-oriented than other traditional sectors in AEC. It is partially true that only a few manufacturing-oriented sectors (e.g., the steel construction sector, the kitchen cabinet sector, and the staircase sector) in AEC have been very successful in adopting new technologies. However, in contradiction to common perception, the precast concrete sector is much closer to the traditional AEC sectors than to the manufacturing industry. Precast concrete pieces generally cannot be mass-produced and are unique by project. Thus, the success of this project suggests the potential of applying similar technology to broader AEC sectors.
Design systems with the capability to store and manage such complex design and engineering information are called *Building Information Modeling* (BIM) systems. However, we only have the outlines of BIM. There is much work to be done by academia and industries to turn the BIM technology into a practical solution for different sectors of the construction industry.

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