SPATIAL ANALYSIS FOR TILT-UP CONSTRUCTIONS BASED ON A CASE STUDY

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ABSTRACT

Building using Tilt-Up concrete panels is a technique that allows contractors to erect facilities in a short period of time because of the simplicity of the method. Each year the construction industry builds more than 10,000 tilt-up panel structures covering more than 60 million m^2 (650 million square feet). Architects have the challenge of producing harmonic designs that fulfill client's needs and expectations and breaking the "box structure" paradigm that has traditionally defined tilt-up.

This paper focuses on spatial analysis of the bracing system for tilt-up constructions and tolerable clearances between the lifted panel and the on-going structure. 3D and 4D-models were developed in order to minimize the time spent on installation and the expense of temporary support materials used during the placement of concrete panels such as steel braces, concrete deadmen and foundation walls. This paper is based on a case study of the construction of a unique 1,670 m^2 (18,000 square feet) residential facility requiring more than 500 m^3 of concrete (17,470 cubic feet) and consisting of more than 2,400 m^2 of panel surface area (26,200 square feet). The facility is composed of 108 concrete panels connected together like a jigsaw puzzle. The greatest challenges of the job were the requisite high joint connection accuracy of 1.27 cm panel to panel (half an inch) and the task of building the structure in accordance with architectural and engineering demands.

KEY WORDS

3D and 4D Models, Bracing System, CAD Visualization, Computer Animations, Planning Design, Space Handling, Spatial Analysis, Tilt-Up Panels.

INTRODUCTION

Implementation techniques in construction procedures have been a central focus of the industry as of late; one of these great tools is Computed Aided Design (CAD). Computers are enabling Project Managers to improve productivity, allowing them to simultaneously optimize their use of materials and equipment and save time on installation procedures.

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CAD tools are being used to visualize construction operations, permitting the analysis of complicated on-site procedures to take place first in an office. Successful construction operations coordinate the complex interactions between multiple pieces of equipment, labor trades, and materials (Kamat and Martinez 2001). Computer simulation and animations provide users a new way to analyze a composition of the different elements playing a roll in a unique environment; 3D modeling generates spaces that can be as accurate as real life. More and more users have become addicted to computational software owing to the fact that analyzing an operation in the office, as compared to improvising the same operation on-site, reduces costs substantially. Planning construction projects during the 90's did not involve complete reliance on simulation methods (Tucker et al. 1998); but with the advances in technology that have been occurred during the past 10 years, computer applications have changed the industry. Simulation modeling and visualization substantially assist in the designing of operations and in making optimal decisions, whereas traditional methods prove ineffective or are unfeasible (Kamat and Martinez 2001). Any CAD software is based on input data (3D information) given by the user; it would behave more realistically if its graphic representations and user applications better reflected the customer's needs and could be applied without extensive effort. 3D and 4D models have then to work like an automated system that integrates as many disciplines as possible to provide a broad view of the situation. Some researchers in the mid 90's believed that these systems had created "islands of automation" and are far from achieving an acceptable level of integration across the design and construction processes (Kartam, 1994). This insufficiency has been improved in recent years, linking all disciplines involved in the construction field; an extensive body of research has been done regarding automation and computer analyses based on 3D modeling and integrating systems (Bjork, 1989; Ammermann et al, 1994; Aouad et al, 1994; Tracey et al, 1996; Wix, 1997, Ekholm and Fridqvist 2000, and Zhong et al, 2004).

The combination of 3D modeling and optimization techniques can provide a wide range of possible solutions that would open different perspectives when making managerial decisions. In order to do so, a combination of the CAD geometrical space and a syntax or optimization procedure has to take place. There is a lack of connection between these two parts in many construction companies; the problem with current project planning techniques is that they do not include spatial requirements of construction operations as a resource in their scheduling (Mallasi and Dawood, 2002).

4D models help to visualize space constraints during installation procedures, allowing contractors and the parties involved to analyze in detail any possible change before performing the operation on-site. Most of the software available in the market right now generates benefits by integrating schedules and 3D models and rehearsing different 'what-if' scenarios for coordinating site operations and communicating the project plan in 4D (Mallasi and Dawood, 2003, Akinci, et al 2003, and Zhang, 2005). Simulation and computer animations integrating CAD packages are becoming useful tools that can show relevant information to enable a better understanding of the construction process, better estimating of cost, and a more appropriate planning (Xu and AbouRizk 1999). The aim of future research has to be the integration of all components required to construct any facility in 3D and 4D spaces allowing changes if needed; it has to behave as a virtual building laboratory for the concurrent simulation of all components (Zimmermann, 2003).

For complicated construction projects where many multi-activity tasks take place in a predefine area, 3D and 4D models help to minimize inconveniences with regards to space constraints. Current industry practice lacks a formalized approach or a tool to help project managers analyze spatial conflicts between activities prior to construction (Akinci, et al 2002). Unfortunately, at this point in time, many construction companies do not integrate computational models with construction schedules and cost controls; conventional models govern the way constructors build facilities; planning procedures are not based on 3D or 4D models, precluding the chance to reduce problems on-site.

This paper focuses on how to manage Tilt-up constructions with spatial constraints; it discusses a procedure that saves time and effort by implementing a plan for bracing concrete panels before the installation takes place based on 3D and 4D analyses. With more than 60 million m^2 (650 million square feet)[5] of facilities constructed per year, Tilt-up has the potential to build structures in a relatively short period of time.

CASE STUDY

The facility used for the case study is a unique private facility in New York that has been in construction since June 2004. Designed by Steven Holl [Web-1], this facility uses a construction methodology based on tilt-up panels, which uses reinforced concrete panels that are cast and cured on-site and then lifted with a crane. With more than 1670 m^2 (18,000 square feet) in footprint area, this facility comprises four pavilions and includes a library, garden house, gallery and sport and entertainment facilities. Robert Silman Associates and DSI Engineering developed the structural design for the facility (Figure 1).

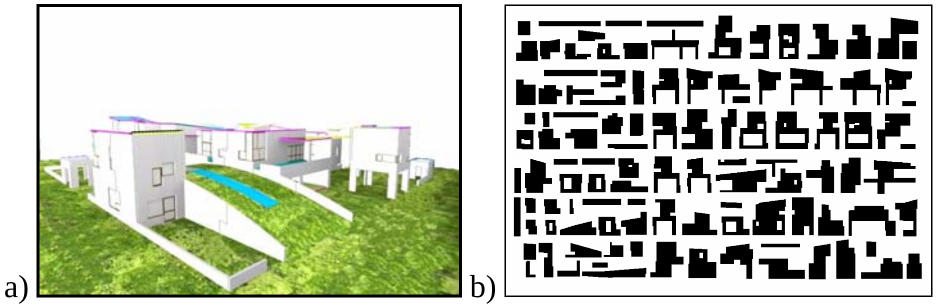

Figure 1: a) Architectural model, b) 108 concrete panels used for the case study

This complex project includes 108 tilt-up panels as shown in Figure 1, and is unique in terms of the jigsaw-like shapes, all of which have a different sizes and weights. Many of these panels exceeded 10 x 10 m (35 x 35 ft) and weighed from 1,356 kg (3,000 lb) to 27,572 kg (61,000 lb). Most of the panels have a thickness of 20 cm (8 in), but some are as thick as 27.94 cm (11 in). As shown in Figure 1b, each panel is unlike the other, presenting challenges to interlocking them as one unit. The architectural requirements of the project necessitated the use of a tilt-up construction method. As mentioned before, 1.27 cm (0.5 in) joints separate the ends of the panels from each other, increasing the difficulty of the

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[5] Tilt-up Growth Continues Due to Speed of Delivery, Cost-Effectiveness and Increased Acceptance, Kimberly Izenson, CPSM, DCD Design Cost Data www.dcd.com, January 2006

construction and installation process. Some of the panels interlock on the same plane; others interlock at 90 degrees in corners and as a consequence, have their end sides exposed (Figure 2). The main reason for constructing casting beds was to transpose their flat and smooth finish onto the concrete panels. The end sides of the panels were not in contact with the casting slab, but they were in contact with the forms. Special form liners were used to provide smooth side surfaces and rounded corners. The advantage of using form liners is that they provide a more even surface than the casting beds themselves. For windows and some special doors, tapered radius corners were not used because of future frame installations.

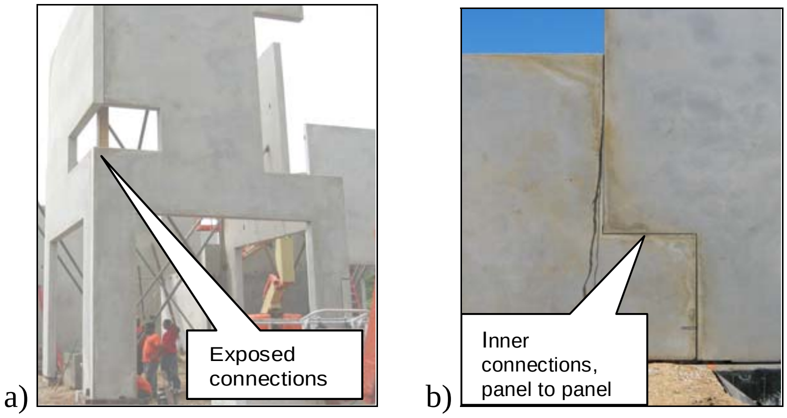

Figure 2: Panel connections

Due to space constraints, short time for the erection process and high equipment costs (crane rental costs), the construction layout needed to be as simple as possible to minimize the constraints for the lifting process. The construction process required a high-capacity crane for panel installation. The strategy was to rent a crane with the lowest rental cost possible, but with the capacity to lift and place all the panels in their final locations. A crawler crane was selected for this purpose (Manitowoc 888 [230 tonnes]). This lifting process required an optimization model to minimize crane displacements and to ensure better use of the concrete required for the casting slabs (Manrique, et al 2005). The final layout with the concrete panels' locations on the casting bed was the key in enhancing the installation process (Figure 3). The numbers on Figure 3 describe the crane picking/lifting points for the different subgroups of panels. Optimizing crane selection and utilization on-site is described in detail in (Manrique, et al 2005). The complex nature of this project posed a challenge to optimize the construction process. Erecting tilt-up panels is not a widely used technique for residential construction, especially for buildings with panels that have irregular shapes. Evaluating the constraints before tilting up each panel not only reduced cost, time and labor, but the quality for the installation became more reliably corresponded with acceptable tolerances. Several layouts with different casting bed shapes and different panel locations were proposed and experimented with during the planning stage. The casting beds were placed around the facility, allowing the crane to move between the house and the cast panels. This path (dotted line in Figure 3) had a width of 14 m (46 ft). One of the main reasons for leaving such a distance between the crane and the structure was the weight pressure that would be exerted by the crane against the footing and the basement walls.

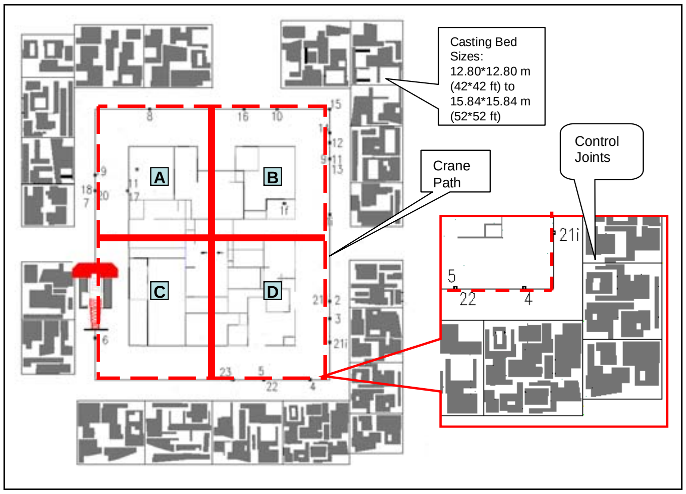

Figure 3: Construction layout

The casting bed sizes range from 12.80 x 12.80 m (42 x 42 ft) to 15.84 x 15.84 m (52 x 52 ft). The total casting bed area was 4,316 m^2 (46,458 sq ft). To avoid cracks and fissures, the geotechnical engineer required that the crane, for safety assurances, should keep a minimum distance of 3.65 m or 12 ft from the foundation walls.

A mock-up model was designed and built to minimize imperfections during construction. There were many uncertainties to address and many risk factors that could precipitate the failure of the project: that is why a smaller model was constructed to manage the risk of material selection and the erection procedure. Many characteristics were explained during the conceptual planning and feasibility analysis phase and many parameter considerations for the mock-up model were included such us space constraints, bracing system, lifting equipment, materials and forms. The model comprised five concrete panels, comparable to those in the actual structure, with window and door openings and rectangular and diagonal shapes as shown in Figure 4. The dimensions of this mock-up model were 3 x 3 x 3.65 m in footprint (9.8 x 9.8 x 11.9 ft). The panels were one-third the size of an actual panel. The steel braces ranged from a length of 4.26 m (14 ft) to 9.75 m (32 ft), with nominal diameters up to 20.32 cm (8 inch); space constraints could pop up if no attention were to be paid during the installation (Figure 5).

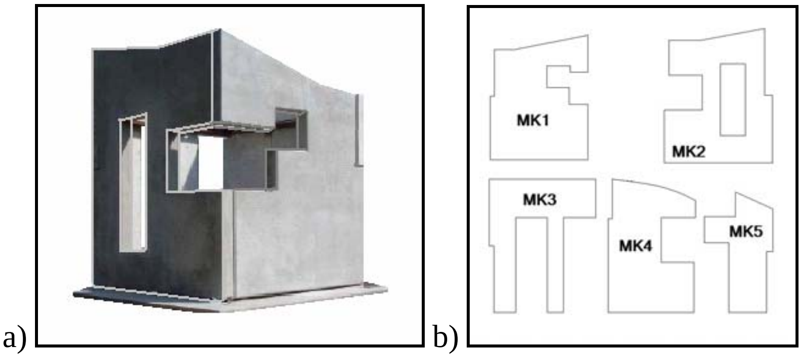

Figure 4: a) Mock-up model, b) Layout of the panels used

Figure 5: Bracing the concrete panels

PROPOSED METHODOLOGY

In order to minimize material expenditure and installation time, a structured procedure was followed to achieve expectations and to provide possible solutions regarding space constraints and brace maneuverability. As can be seen in Figure 6, information was gathered from the mock-up model, the 3D (CAD) model and the bracing requirements for each of the panels. Utilizing a spreadsheet, data was managed to produce a complete list of the material needed, including spatial locations, amount of concrete deadmen, and brace types. A 4D model and computer animations were incorporated at the end of the exercise to show possible constraints during the installation procedure. With the help of Common Point 4D[6] and Microsoft Project, the 4D model showed in sequence a plan of how the panel installations were to proceed, allowing managerial decisions to be based on planned solutions before every lift.

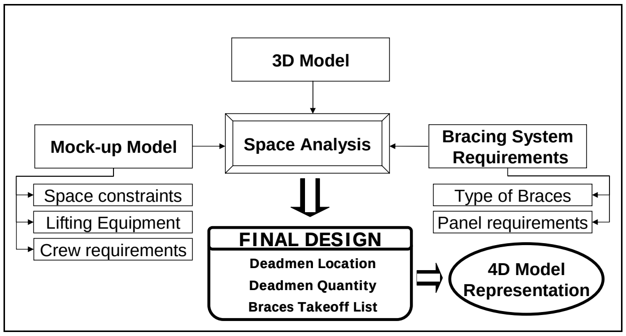

Figure 6: Proposed Methodology

The installation procedure of the concrete panels required for this project was sorted upon structural needs. The facility was subdivided into 4 areas (as can be seen in Figure 3) with two lifting phase sequences. The two lifting phases were organized in such way that the pier panels in each area had to be installed first, and then, the light panels that enclosed and connected the entire structure were set on top. In the first phase, the four areas worked independently from each other; this fact provided the opportunity to maximize the equipment

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[6] Common Point 4D V.1.95, www.commonpointinc.com

utilization and crew adaptation by starting with a sector with less operational demands. Because of the uniqueness of the project, the crew had to be introduced to the operation before it started. This was conducted in two steps: first, creating computer animations (Manrique, et al 2005) and, second, analyzing the bracing procedure with the installation manager, which is the focus of this document. DSI Engineering designed the concrete panels, providing brace types and dimensions, and anchor locations. By the time the installation procedure took place, the slab on grade on top of the foundation walls was not poured yet, forcing reanalysis of the anchor location of the bracing system. In order to start with the analysis, four modules were utilized: the bracing system, the 3D model, the 4D model and the mock-up model results.

Bracing System. The braces required for the job had constraints including:

- Inclination angle between the floor and the brace: 40-60 degrees.
- Maximum opening angle from the perpendicular of the panel: 5 degrees.
- Brace nominal sizes: 4.26 m (14ft), 6.70 m (22 ft), and 9.75 m (32 ft).
- Maximum Brace extension/contraction: ± 5inches (Figure 7).

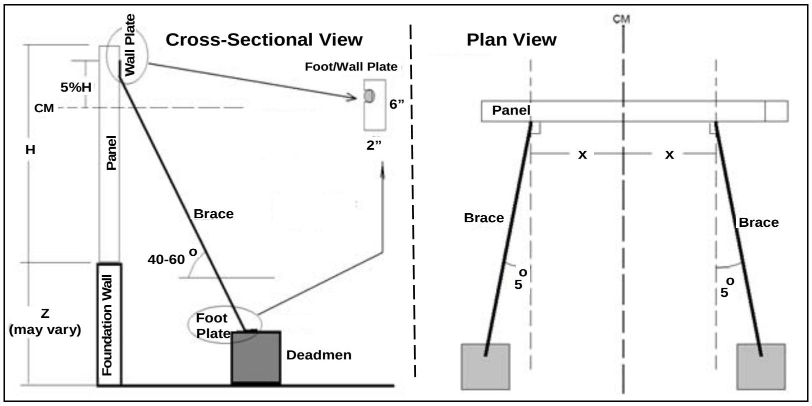

Figure 7: Bracing system

The braces had to be anchored to the panels and to the deadmen/foundation walls with 1.9 cm (¾ inch) diameter expansion bolt heads with a length of 12.7 cm (5 inch). Most of the panels due to the absence of the slab on grade had to be anchored to concrete deadmen with a max volume of 0.76 m^3 (1.05 CY).

3D Model. The constraints mentioned before regarding the bracing were modified based on the crew installation experience and the 3D model to find the possible location for the foot plates (Figure 8). The maximum opening angle of the panel from the perpendicular was exceeded in order to minimize the amount of deadmen, then the foot plate of the brace was anchored to the foundation wall or footing depending upon the scenario. In order to keep the brace angle range between 40 to 60 degrees with respect to the floor, 9.75 m braces (32 ft) were used for some of the panels. Using CAD, the final location of the foot plate/deadmen was found, simplifying the installation procedure (Figure 8).

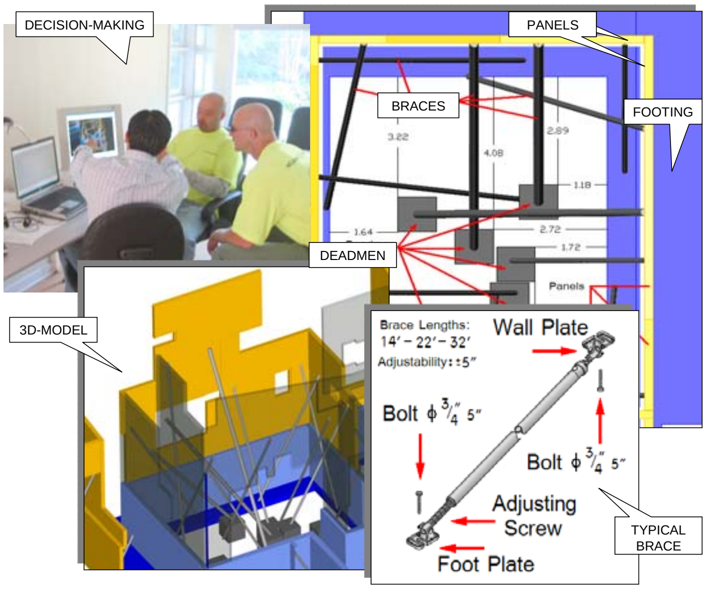

Figure 8: 3D CAD Model

4D Model. Due to the considerable number of braces required to support the concrete panels in certain sectors of the construction site and because of the possible space interruptions between braces when installing the panels, a 4D model was developed based on the structural sequence and the crew adaptability to the process. During the simulation process with the 4D model, some of the braces had to be relocated because of the spatial interference between braces, the lack of space for deadmen, and the difficulty of installation (Figure 9).

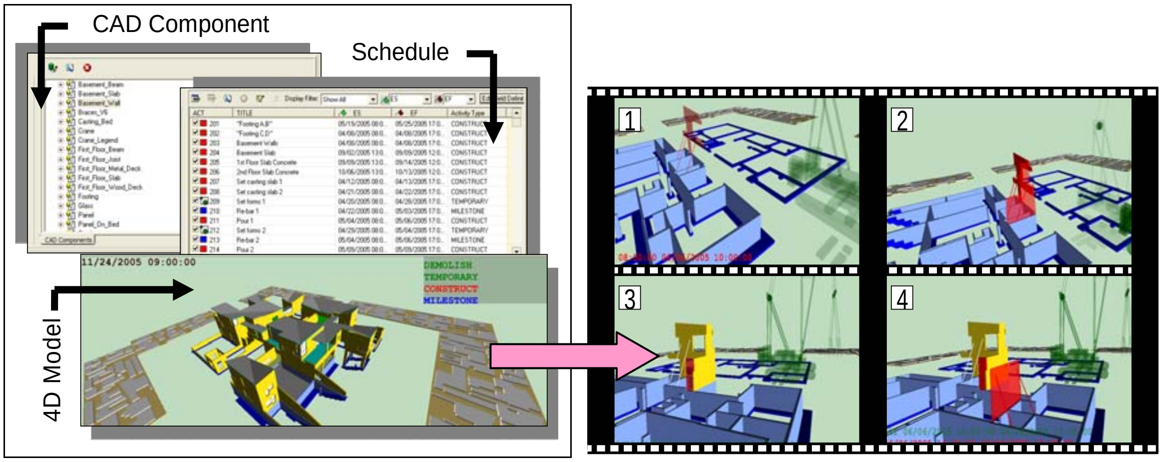

Figure 9: 4D Model (Panel Installation)

Occasions such as multiple deadmen in a row were managed using a Jersey barrier which is a pre-cast concrete barricade used to separate lanes of traffic. Figure 9 shows the software interface (Common Point 4D) which combines information from the schedule (MS

Project) and the 3D model (CAD Model), providing as output a 4D model that shows the installation process through time. Bearing in mind the constraints related to minimum clearances between the lifted panel and the on-going structure, the length and location of the braces on the panels were tested with an animation process (Manrique, et al 2005). Both models show possible errors during the installation procedure, but the development of computer animations demands more time than utilizing 4D models.

CONCLUSIONS

3D models (CAD Spatial analysis) and 4D models were used to plan, ahead of time, a complicated tilt-up installation process regarding the bracing system. A systematic model was developed to minimize material expenditure (concrete deadmen) and to obtain the final bracing location in 3D space. Because of accuracy requirements, every lift was analyzed on the computer screen before the actual construction, providing directions to the lifting/bracing crew for the installation. Errors were encountered during the installation of the first seven panels because of a misplacement of center chalk lines; as a result, the installed panels had to be removed, re-installed and re-braced. The results obtained for the installation process are as follow: twenty seven 0.74 m^3 concrete deadmen, two Jersey Barriers and one hundred and twenty six steel braces were used. With the systematic model, it was possible to save 99 concrete deadmen, and facilitate the bracing regarding the installation process. The 4D model demonstrated to the crew possible alternatives to deal with the installation and helped to make managerial decisions in advance.

LIMITATIONS

A spatial constraint solution can be made by re-adapting the bracing position on the panel (wall plates) and by minimizing the use of deadmen via an optimization model. The lack of time and predefined structural requirements made it hard to develop an approach other than the one presented on this paper.

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