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A Case Study of Materiality and the Necessity of Craft in the Age of Digital Fabrication

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Abstract

Digital technologies have opened up a vast array of possibilities with respect to architectural design and fabrication. Architects must be wary, however, of not only the possibilities but also the limitations inherent in digital fabrication methods, particularly the continued need for trial and error and craft as integral parts of the construction process. We tend to extend the precision of digital fabrication to all aspects of buildings that incorporate these technologies and forget that, at least for the time being, the building process is still subject to the vagaries of weather, human error, and site conditions.

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Digital technologies have opened up a vast array of possibilities with respect to architectural design and fabrication. Architects must be wary, however, of not only the possibilities but also the limitations inherent in digital fabrication methods, particularly the continued need for trial and error and craft as integral parts of the construction process. We tend to extend the precision of digital fabrication to all aspects of buildings that incorporate these technologies and forget that, at least for the time being, the building process is still subject to the vagaries of weather, human error, and site conditions.

Important relationships that continue to exist and therefore should be acknowledged and understood by architects include how digitally designed forms are translated into material components, how digital information can be communicated, how installation methods should be determined, and how unpredicted changes can be accommodated. The more architects can anticipate these factors and build them into their designs and specifications, the more smoothly and effectively the final project can be realized.

This paper will use the 10,000 square meter glass and steel atrium roof of the Zlote Tarasy complex in Warsaw, Poland, completed in 2005, to illustrate some of the disconnects as well as opportunities possible between design, fabrication, and construction in digitally-based projects.

FORM AS GENERATOR

The ability to transmit numeric data from a three-dimensional computer model to fabrication equipment allows structures of virtually unlimited complexity to be fully realized. But a 3D design model is not enough to produce actual building elements. One danger of the apparent ease of digital fabrication is that it gives architects the possibility of becoming pure form-makers without consideration of the complexities of materiality. The lack of consideration of the fact that the lines of the design model would ultimately represent real material with real dimensions and properties led, in the case of the Zlote Tarasy roof, to misunderstandings that caused delays, additional costs, and possibly reinterpretations of design intent.

The undulating form of the Zlote Tarasy roof was initially developed by draping a virtual "cloth" over eleven spheres to create an undulating, irregular surface in 3D Studio. The designers likened the form of the roof in combination with its branching "tree" columns to a forest canopy that would "combine nature with retail and entertainment" and recreate the ambience of an external shopping center in a fully climate-controlled environment.

While its form was being developed by the designers, the roof was represented solely as a net of lines without dimension. When the three-dimensional model was taken over by the project's structural design engineers, the only criteria given by the architects was that the net maintain its original configuration as closely as possible and that the surface be continuous, without movement joints. As a result of discussions during design development, it was determined that the roof would be a net of steel members that acted as a single structural element, allowing movement only where the steel net met the concrete structure of the surrounding buildings. In order to calculate the forces in the various members, the lines of the design model had to be translated into dimensional steel. Were the lines in 3D Studio the joints between glass panels? Or the centerlines of the steel members? Or the centerlines of the bottom or top surfaces of the steel members? Ultimately, as the design of the glazing system had not yet been considered and therefore could not be given dimension and as the structural engineers were primarily concerned with the steel components, they decided that the lines in the model would represent the centerlines of the steel members.

Fig. 1. Rendering of the Zlote Tarasy atrium roof at the main entrance

A three-dimensional model of the roof was then constructed and structural design calculations proceeded accordingly. It was determined that the roof would be made up of rectangular steel sections 50mm wide by 100mm high. At this point, the architectural designers became concerned that the interpretation of their model as representing the centerline of the steel members would lead to a distortion in the geometry of the net. They had thought of the net as the representation of the visual quality of the roof when viewed from the exterior (or the interior, depending on the view being considered) and thus the lines would be the joints between glass panels. It was not possible, however, to revise the model to represent this because the glazing system had not yet been designed and the thickness of the glass and its support system were unknown. The model was therefore revised so that the lines of the original 3D Studio net represented the centerlines of the top of the steel members. This significantly impacted the structural calculations and required their complete revision. Had the design architects considered their design as a material thing with dimension rather than just an abstract shape made of lines, much confusion could have been eliminated.

DOCUMENTATION

The realities of the ways in which elements are fabricated using digital methods also requires re-thinking of construction documentation and construction administration, particularly the submittal and review of fabrication and installation documents. The Zlote Tarasy contracts required that all structural calculations and shop drawings were to be reviewed by the design engineers and executive architects. In a pre-digital project, sets of documents showing the detailed engineering, material qualities, and dimensions of every type of component would have been submitted for review and comment and eventually signed off for approval. At Zlote Tarasy, each one of the approximately 10,000 steel sections had ends that were dimensionally unique, each connecting node was geometrically unique, and each element had a unique combination of forces. To convey this information in traditional documentation would have required tens of thousands of drawings and at least as many pages of calculations.

To prepare and process this kind of documentation would have required untold reams of paper and hours of review time. Furthermore, such documents would not be used in the actual fabrication process because the data contained in the engineering model could be directly transmitted to the fabrication equipment. As a result, the review of contractors' documents shifted to a review of methodologies, electronic comparisons of calculations, and numerous quality controls put in place during both fabrication and installation. This process presented several advantages. For example, time in the past spent reviewing shop drawings could be reduced to a minimum by limiting such review to method statements describing fabrication and installation processes and a minimal number of drawings required for construction coordination. Furthermore, the production of these documents by the contractors required thorough consideration of their construction methods and detailed coordination with sub-contractors to ensure that all proposed methods were in fact feasible prior to start of construction. Because the review process differed from the requirements of the contract documents, the specifications had to be amended to reflect the revised process. As digital fabrication becomes more commonplace, these changes in review requirements will undoubtedly become more ubiquitous and mid-project contractual changes less frequent.

FABRICATION

As mentioned above, each of the thousands of steel members and nodes that make up the Zlote Tarasy atrium roof structure is dimensionally unique. In the past, the production of such complex shapes was limited in that steel elements, for example, could be efficiently fabricated only if the same cuts were repeated multiple times and the number of different cuts was limited so as to maintain reasonable fabrication time and costs. Furthermore, such cuts were typically made on site rather than in a workshop, increasing both the time required for construction and the possibility of error due to site conditions. With digital fabrication, every component can be unique as the amount of time required for unique individual cuts is generally no different than that required for repeated cuts. This facilitates the realization of complex geometric forms that depend upon angles and shapes that are non-repeating.

In the case of the Zlote Tarasy roof, a digital model was created that included every component of the roof structure and enclosure down to the smallest screw. The electronic data from the model was then fed directly to the cutting machines so as to eliminate the possibility of human error. This was critical because the cutting tolerance for the steel elements could be no more than one millimeter in any direction to prevent larger discrepancies from occurring at later stages of fabrication and installation.

According to the designers of the atrium roof, the highest priority for its construction was the maintenance of the seamless visual continuity present in the original modeled version of the net. When the roof specialists began building an actual dimensioned model of the roof on the computer, they discovered that in areas where members "curved" away from nodes in multiple directions, large portions of the steel nodes would project out from the underside of the net. This was unacceptable because the nodes in these situations could potentially cast shadows on the surrounding members and disrupt the apparent fluidity of the roof. To correct this, the nodes had to either become large, visually distinct joint elements that could incorporate the shifts in angle or they had to be cut in three dimensions so that the node arms would more closely follow the angles of the surrounding members.

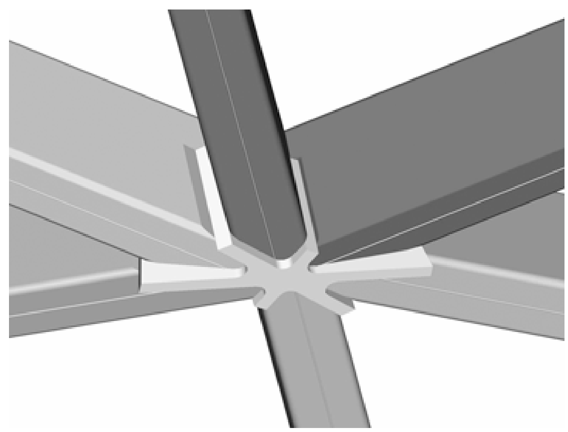

Fig. 2. Node with undesirable projections

While it certainly would have been easier and cheaper to produce the more distinct joint elements, this option would not have produced the desired visual quality for the roof. To produce the three-dimensional nodes, both the programming and the cutting machinery had to modified to cut in three dimensions. For the typical nodes, the digital configuration of each node was transmitted to a cutting robot which then cut the node from a steel plate by moving parallel to the surface of the plate. For the three-dimensional nodes, a welding robot whose arm could turn while welding was modified to cut steel using digital input. This required a considerable amount of programming and testing on the part of the fabricator to ensure that the required tolerances could still be achieved. At the end of the day, a compromise had to be reached between the contractors and the designers to allow a determined amount of projection in the nodes. With this agreement, only about forty-five per cent of the nodes were cut three dimensionally and, as this cost was not assumed as part of the initial contract, considerable cost overruns were ameliorated. At the same time, some visual continuity had to be sacrificed and additional costs were incurred by the roof specialists and fabricators because of the time required to develop the new system as well as the additional coordination required for the more complex node production process.

SAMPLES AND QUALITY CONTROL

The review of control samples has long been an important part of construction administration. With digital fabrication, it is even more critical to review samples not only for their material qualities but also as a check of fabrication processes. Furthermore, given the complexity of digital fabrication processes it is crucial for architects to incorporate additional requirements for quality control into their specifications to ensure that problems are discovered early.

The glazed enclosure of the Zlote Tarasy atrium roof consists of approximately 4800 triangular insulated units, each of which has a unique shape. As with the steel elements, the glass was cut by machines driven by electronic data taken directly from the computer model. A ceramic frit pattern in three different densities was applied to approximately sixty per cent of the glass units to reduce heat transmission.

Samples of all glass units were required for submittal and review. Samples were not required, however, of full glazing units and only one sample of each glass type was required. This enabled the architect to check the visual quality of the glass but did not consider fabrication problems that could result from the lack of geometric repetition.

During glass production, a significant quality control issue arose as a result of the clash between the geometric uniqueness of each unit made possible by digital fabrication techniques and the material realities of the frit application process. To apply the ceramic frit to the glass panes, the glass producers used a typical silkscreening process where ceramic paint was applied to the glass using a rectangular screen that could accommodate the full range of glass sizes. The problem occurred when a larger glass triangle was printed after a smaller one. In printing the smaller triangle, the paint was applied uniformly over the entire surface of the screen and then rolled onto the glass surface. For the next triangle, the same procedure was carried out but, if the second triangle was larger than the first, the excess paint that had not been rolled onto the smaller triangle would then be rolled onto the larger triangle, causing the dots of the frit pattern to run together and create dark zones on the glass. To correct this problem, the order of glass production had to be altered and additional cleaning prints had to be made to prevent the build-up of excess paint on the screen. About 2300 glass units had been produced and several hundred had been delivered to site. Because the glass fabricators were not required to keep detailed quality control records, the only way to determine which panes were flawed was to inspect each one individually.

It is important to consider the role of the digital framework of the project in this regard. Because of the extremely sophisticated computer modeling used to fabricate the building components and the minimal tolerances that could consequently be achieved, the project team was put at ease by technological prowess and neglected to some extent the fact that the materiality of building is still a reality that does not necessarily conform to the idealized parameters of the digital world.

CRAFT AND THE NEED FOR PROTOTYPES

The accuracy of digital fabrication and pre-assembly of elements off-site can significantly increase the precision of construction on site. This does not, however, eliminate the need for skilled craft in the field. Human beings are ultimately doing the installation work and because of the tight tolerances achievable digitally it is all the more critical that installation be accurate. Understanding where pre-fabrication can be implemented and where errors can occur on site can be facilitated by prototype production and testing. It is particularly critical that the same site conditions and personnel be used, as much as possible, to construct mock-ups as to produce the actual building.

No matter how meticulously a project is designed on the computer, if it is ultimately to be realized in real materials it must be tested to prevent significant costs and delays. The gasket system of the Zlote Tarasy atrium roof perfectly illustrates this situation. The roof's glass panels are carried on silicone gaskets and sealed with liquid silicone to form a weathertight enclosure. Like the steel rectangular hollow sections and nodes, each linear gasket segment and each gasket connection is unique. Because of dimensional variances in the steel installation as well as issues with site coordination, the gaskets were not prefabricated off-site to conform to the roof geometry. Standard elements were instead delivered to site where they were cut to fit each condition and sealed by hand using liquid silicone.

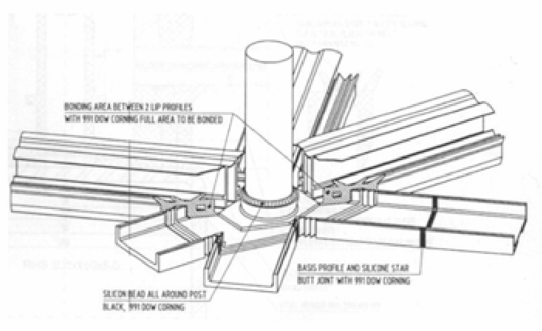

Fig. 3. Gasket system

Because of the varying angles that occurred at the nodes, a special star-shaped gasket was developed by the engineering designers with accordion folds built into the corners to allow the stars to be bent and twisted to suit each condition. In the course of building a test mock-up, it was discovered that unanticipated problems were occurring with the star gaskets. Because of the varying node geometries, the folds in some stars could not be compressed tightly enough to achieve the required configuration while others had to be stretched to the point of tearing. Furthermore, the stars had to be temporarily held in place with an evaporating glue because they tended to spring back into their original configuration. To solve these problems, several new node stars were developed with folds that tapered in different directions. The temporary glue also had to be tested and approved for compatibility with the intumescent paint used on the steel structure.

To maintain watertightness, each linear segment of the two-component gasket system had to be field measured, cut to length, and sealed with liquid silicone. To do this accurately required experienced installation personnel. During the mock-up construction, for example, it was discovered that poorly crafted gasket joints led to the build-up of excess silicone that blocked the drainage lines built into the gaskets.

As can often be the case, the atrium roof contractor did not feel it was necessary to build and test a mock-up of the roof as they had built similar structures before. Because the technical architect incorporated prototype testing into their specifications, the contractors had to comply and actually saved themselves both time and money by discovering flaws of both design and craftsmanship that were not expected because of the precision of the digital modeling and fabrication.

CONSTRUCTION

No two worlds could be more different than the ideal conditions of the computer model and the real conditions of the construction site. In the model, every concrete pour is perfectly accurate and level, every day has perfect conditions, and every worker has equal and ideal skills. On site, no matter how sophisticated the design may be, the realities of material, weather, and human error become major players.

At Zlote Tarasy, the beginning of steel installation was delayed for two months because of delays in engineering the concrete slabs. Additional reinforcing had been added near many slab edges, resulting in conflicts with the anchor bolts for the vertical atrium roof supports. Fortunately the steel installation system could accommodate such discrepancies. Approximately two-thirds of the steel members and nodes were pre-assembled off-site into 129 steel ladders. These were installed on temporary props on site and the gaps between them filled with loose steel members. This step was critical because it was here that adjustments were made to accommodate installation tolerances. The loose members were cut down if too long or plates were added at weld points if too short. Each site weld then had to be inspected and tested according to a series of protocols. This system allowed the final built geometry to reflect the designed geometry as closely as possible in that it distributed dimensional discrepancies across the entire net. Had the ladders been welded to each other or the entire net assembled with individual pieces on site, the tolerances would have accumulated from one side to the other, affecting interfaces with surrounding construction.

Fig. 4. Steel ladders installed on site

Because of the delay in the start of steel installation, the installation of the glazing system was also delayed. Originally scheduled to being in mid-June and finish by the end of October, gasket and glass installation did not begin until late August. This led to serious problems later in the year because the liquid silicone specified could not be used below 0° C and had to be applied under dry conditions. As fall and winter in Poland tend to be quite cold with considerable precipitation, this quickly became an issue potentially delaying not only the roof construction but the rest of the project as well. While the actual installation time was ultimately extended somewhat, major problems were avoided by the installation team. Their supervisors, experienced craftsmen who had just come from the Swiss Re tower in London, were aware of a silicone that would cure properly at lower temperatures. They also developed a system of coverings for the roof that protected the installation from precipitation and allowed work to continue. These solutions were the direct result of the experience of the personnel on site and as such should certainly be considered as part of the craft still required in construction despite the precision of digital fabrication.

CONCLUSIONS

The use of three-dimensional computer modeling has allowed architects to expand the complexities of building form and spatiality not only by making the design of complex forms and conditions more accessible but, perhaps more importantly, by making their construction and thus their use and inhabitation a reality. If an architect feels, however, that he or she can now turn over attention to construction details and processes exclusively to the fabricators and contractors, he or she will be sorely disappointed. If anything, the understanding of the construction methodologies and level of craft required by digitally determined projects are even more critical to the work of the architect. Until we find a way to erect buildings with robots in completely controlled environments, the ingenuity of human craft and experience will remain a fundamental part of the building process. Were we to give this up, we would lose the fundamental humanness of design and construction.

Fig. 5. Interior view of the completed roof