Master Architect Redux:
How Digital Progress Helped Restore the Role of Master Architect

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> *...today, the roles of architect and builder are formally dissolving: the architect designs the building but then gives up control and becomes a design consultant who does not actually stamp the drawings; and the contractor gives up control by passing liability along to subcontractors and manufacturers.*
> —*Howard Davis*, The Culture of Building, *1999*

> *The new computer and management system allows us to unite all the players – the contractor, the engineer, the architect – with one modeling system. It's the master builder principle...the reverse of the twentieth-century system.*
> —*Frank Gehry*, Gehry Talks, *1999*

INTRODUCTION

Examine the work of Frank O. Gehry and Associates and you will find a twenty-first century architect with the mind-set of a medieval master mason. Gehry has often been quoted as heralding the computer -assisted return of the "master architect". One might have expected that Gehry would be anticipating the future with his state-of-the-art software, but ironically his new-found power is being used to move back in time to reclaim the long-lost role of the master builder.

This paper will examine how the role of the architect has progressively gained more legal definition while paradoxically losing decision-making power in the actual building construction process. The Experience Music Project, recently completed in Seattle, will be used as one example of Gehry's attempts to reverse this trend and regain a central role in the construction of his buildings through the use of the computer model as a reincarnation of the full-sized template.

HISTORY: THE GOOD OLD DAYS

There was a time when the architect was the lynchpin to any construction. The demise of the Greek "tekton" (master constructor)–replaced by the litigation-constricted lackey of developers and bankers – is a sad story. Increasing specialization, shortened time frames for construction and the need to limit liability exposure are but a few of the contributing forces. Architects have become marginalized in the building process, relegated to the role of the conceptual designer who must rely on others to translate the vision to built reality. Since the nineteenth century, the roles of architect and builder have become more defined and the architect has gradually lost control over the construction process.

There were two time periods where the role of the architect/builder was the most central powerful position in building culture. One is embodied by the master builders of the Middle Ages, the other by the precursor to the modern practice, the late nineteenth century firm McKim, Mead and White.

In the Middle Ages, undertaking to build a cathedral was the most challenging endeavor that a builder could face. The medieval master mason closely resembled the Vitruvian ideal of an architect:

> *Him I call Architect, who by sure and wonderful Art and Method, is able, both with Thought and Invention, to devise, and, with Execution, to complete all those Works, which, by means of the Movement of great Weights, and the Conjunction and Amassment of Bodies, can, with the greatest Beauty, be adapted to the Uses of Mankind: And to be able to do this, he must have thorough Insight in the noblest and most curious Sciences.*[1]

Through a system of apprenticeship and training by means of empirical testing, the master masons grew into a role that we would now think of as the architect's[2]. In charge of all aspects of building from its form to the construction techniques that would be employed, the master mason was consulted by every tradesman on site for practically every decision. In his book *The Art of Work*, Roger Coleman compares the work of the medieval master with the contemporary architect:

> *The master mason, therefore, was exactly what the modern architect is not: a skilled builder with a mastery of the complete field of building practice. Nowadays no one has the kind of overall grasp of building processes that the medieval mason had, and as a result all manner of faults are built into buildings at every stage from conception to completion. If a medieval mason could build a cathedral then, ipso facto, the whole elaborate business was comprehensible within the traditional skill of masonry, and*

therefore contained in that body of knowledge which constituted the trade of masonry, of which the skilled practitioner was quite rightly acknowledged a master. [3]

The authority of the master mason stemmed from his control over a simple palette of materials. Since the cathedrals used stone and stone only, the men who had mastered stone-work could assume mastery of the whole construction. As the noted historian John Fitchen points out, the knowledge gained through the mason's experience was more reliable than what we can calculate today, the empirical knowledge of the Gothic builders may well have been superior to our present-day scientific computations as applied to their buildings, for this reason: our scientific formulae (which are based upon empirical observation of natural forces, and which undergo revision from time to time as those observations become more exact and comprehensive) are concerned primarily with materials such as steel and reinforced concrete which resist both tensile and compressive stresses; whereas the medieval builders had to solve all their major structural engineering problems in terms of one material, stone, which is trustworthy only in its resistance to compression. Hence the medieval builders came to have the most thoroughgoing and explicit first-hand experience in all aspects of a material that is seldom employed structurally today. [4]

There are no contemporary parallels to medieval stone construction. Rarely do we see monolithic construction today, systems are increasingly specialized with each layer performing its own task and having its own trade (with its own expertise) associated with it. To become the modern equivalent of the medieval master mason, a single individual would have to master *all* the trades for a modern building. This person would have to apprentice dozens of accepted trades and acquire knowledge of new subspecialties that emerge each year.

There are a number of reasons why the master masons did not leave a legacy of master builders. Societal shifts of patronage and building culture during the Renaissance played a large role in this break. But the nature of construction itself evolved slowly enough that it would have been possible for the master mason to transform into the master architect or builder who understood multiple trades involved with multi-faceted construction systems. One of the primary reasons that the legacy was not established beyond the Middle Ages by continuity or apprenticeship was because of the closed nature of the elite ranks of masters. In fact, there were severe penalties for releasing secret information outside the masons' guilds[5] . Historians have long wondered why there are so few accounts of construction from this era. Fitchen attributes this paucity of writing to two factors:

...it is highly doubtful if any but the master masons could have been competent to write a factual account of the specific procedures followed in erecting a building. However, not only were these men too busy to write: above all, they were at once practitioner and custodians of the 'mystery' of their professions, and in both capacities they had a vital interest in not *disseminating the close and jealously guarded trade secrets thorough knowledge of which was held only by these men of superior ability and experience, the masters themselves.* [6]

The aura of omnipotence surrounding the master masons coupled with the fact that they went "extinct" have made many contemporary architects romanticize this era as the apogee of centralized construction power that would never again be matched. Frank Lloyd Wright describes the Middle Ages in glorious terms in his summary of Victor Hugo's *Notre Dame de Paris*.

After seeking the origin and tracing the growth of architecture in superb fashion, showing how in the middle ages all the intellectual forces of the people converges to one point – architecture – he [Hugo] shows how, in the life of that time, whoever was born a poet became an architect. All other arts simply obeyed and placed themselves under the discipline of architecture. They were the workmen of the great work. The architect, the poet, the master, summed up in his person the sculpture that carved his facades, painting which illuminated his walls and windows, music which set his bells to pealing and breathed into his organs – there was nothing which was not forced in order the make something of itself in that time, to come and frame itself in the edifice. [7]

In his own practice and carefully cultivated persona, Wright attempted to craft a position for himself that was closely allied to the ideal he describes above. There were many aspects of a building that Wright assumed under his authority that were not at that time typically considered to be the architect's responsibility. Wright was notorious for dictating the furniture, lights, windows and rugs of the buildings, every aesthetic aspect of their inhabitation. He also became involved with the design and testing of building products and structural forms such as the textile blocks of the Hollyhock house or the mushroom columns of Johnson Wax. His innovative concepts for heating, ventilation and cooling were sometimes more visionary than could be effectively achieved. Both Unity Temple and the Larkin Building were designed with systems that were unheard of at the time. Looking back on these projects today, his logic has been proven correct and the systems he envisioned are strikingly similar to modern HVAC strategies. In fact, Unity Temple was easily adapted to a modern system not long ago, and a contemporary mechanical contractor examining the reflected ceiling plan and building section of Larkin building would find its ducts appropriately sized and logically laid out for the most sophisticated air-handling equipment available today.

THE SLIPPERY SLOPE

In the nineteenth century, the architect emerged as a powerful force in building construction. Howard Davis, in his study of construction culture, pinpoints this time period as critical in the development of the modern architectural practice.

As the nineteenth century progressed, the architect – as a formal institution separate from the building firm – gradually assumed a greater controlling role in the building operation. One needs only to look at the operation of the preeminent New York firm at the end of the century, McKim Mead and White to see this. Every detail and every payment to contractors and subcontractors had to receive the firm's approval; the firm had final say over quality of materials and workmanship; and they produced, for each major building, hundreds of drawings to help them in their control of the outcome.[8]

This power came with a price; as the architect placed more layers of people beneath his power, the distance between the drafting room and the construction site increased. "The architect was at the apex of a hierarchical control system...As the system evolved further, the role of the general contractor grew at the same time as the architect's connection to craftspeople lessened."[9]

Though the nineteenth century architect was in command of the building design and construction, it was a position that had to be increasingly spelled out in multitudes of written and graphic instructions to those in the field. Greatly differing from the constant field-supervision of the medieval master mason, the office-bound architect had to make decisions that were often far removed from the realities of actual construction. Davis describes how another critical legal development changed modern practice:

> *The emergence of the contract [in the late twentieth century]....went hand and hand with an increase in the number of players in a building project. ...As an arbiter of the building contract, the architect was central – but paradoxically, ...the architect's role on the building site was less one of shaping the building and more one of checking on the compliance with the contract.*[10]

The apparent power given to the architect by contractual definition was an illusion. Working within the role of contract administrator, the architect could only exert control through the mediating devices of the contract and the construction documents.

THE CONTEMPORARY CONDITION

Paradoxically, by seeking to rigorously define his role in the contractual definition of the building enterprise, the architect has become completely separated from the construction process. AIA documents specifically seek to protect architects from any decisions made about the construction of their designs, yet also severely limits his power on site. The General Conditions of the Contract for Construction states:

> *The Architect will not have control over or charge of and will not be responsible for construction means, methods, techniques, sequences or procedures...*[11]

The architect and constructor are not only separated by prescribed contractual roles, but there is a wide gap in their thinking processes. Rafael Moneo, in his address to Harvard's Graduate School of Design in 1985, bemoans the mind-set that allows architects to design without an awareness of construction.

> *The intimacy between architecture and construction has been broken. This intimacy was once the very nature of the architectural work and somehow was always manifested in its appearance... to be an architect, therefore, has traditionally implied being a builder: that is, explaining to others how to build. The knowledge (when not the mastery) of the building techniques was always implicit in the idea of producing architecture...Architects in the past were both architects and builders. Before the present disassociation, the invention of form was also the invention of its construction. One implied the other.*[12]

In a similar vein, Renzo Piano, in his article "Have an Idea, Act as an Architect"[13], calls for young architects to view their ideas through the filter of construction. Responding to competition entries that he is judging, Piano criticizes a fashionable belief that the outline of a theoretical idea is enough to be considered architecture, he insists that the true architect considers how it will be built.

REDRESS

The situation today has become so dire that many architects have sought to change the way practice is structured. Some architects, such as those who formulate design/build firms, are trying to change the nature of contractual agreements, serving as both architect and contractor. Since many of the contemporary problems arise from the development of the contract, it is logical that the problem could be solved by a redefining the contractual role in a way that is more favorable to the architect.

Gehry's approach is different than this; he maintains his identity as an architect but redefines it as having a central and powerful role. He has been able to gain control of the building's forms or to be more exact, he controls the *information* needed to build those forms.

Gehry has not accepted the twentieth century definition of the architect but in a sense, favors the role of the master builder. The curvilinear forms of his stylistic language have never been inherently easy to construct, and as the scale and complexity of his commissions grew more substantial, the "fear-factor" of the contractors escalated the bids beyond acceptable levels. In his efforts to get his buildings constructed in a reasonable time frame for a reasonable cost, Gehry has been forced to take on more responsibilities than the architect might normally assume.

These added responsibilities have not been a burden but have proven to be a great liberator for the architect. Gehry relishes his new-found power in the bidding process. He states:

> *...We have to change the way that architect is practiced, because the architect takes the blame for all the market ups and downs...Now most architects pretend that there's no problem and they get the client 'a little bit pregnant,' and then its too late, and then they get blamed, and the profession gets blamed for being a bunch of flakes. When you get a bid from a contractor, you can tell with our system whether or not its an accurate bid if*

the drawings are complete....we are so accurate with the computer that they don't have any wiggle room, because we give them quantities, to seven decimal points of accuracy. It's that clean. It's really precise. [14]

The existing system has been formulated to maintain the status quo and has not been flexible enough to accommodate a different kind of architectural practice. Stepping outside the strictly defined role of the architect, Gehry describes why he no longer counts on traditional systems of legal and insurance protection:

The American legal system, the insurance system and the tradition of the architect-client-contractor relationship are based on a bunch of phony assumptions. After the architect designs the building and does the drawings, he rises from the floor five feet and becomes the holier-than-thou arbiter between the client and the contractor. That's the assumption of the old system. What really happens is that the contractor goes to the owner and says, 'if you straighten out this wall, I can save you a million dollars.' and the client says, 'Wow!' And sometimes he does it. The contractors, because of their relation to money, become parental in the equation, and the architect becomes the child – the creative one. 'Here comes the creative one again: watch out.'

The computer changes the system. We show the contractor the computer model and we show him a wall, built like the most difficult piece of the design. We also give him a disk that says, 'give this to the stonecutter. We want 1,700 pieces of stone double-curved, 800,000 single curved and 800,000 flat of this size.' And the stone cutter says, 'Oh that's not a problem.' He takes a look and says, 'Flat is one dollar, single curve is two dollars, double curve is ten dollars,' multiply that by the areas we've given him, and he is happy. In fact we're doing a lot of the contractor's work. They're happy. They smile. They like it. Now the problem is the insurance companies. This being a legal responsibility, the lawyers say, 'Wait a minute, you're opening yourself to all kinds of lawsuits.' And the insurance company says, 'Wait a minute, you're doing something different. We don't know how to insure this if you're going to take more responsibility.' So it's complicated. But we're doing it anyway. [15]

The most important tool in expanding his role has been the computer and CATIA – the modeling software developed by Dassault for the aerospace industry. The computer is thoroughly integrated in his design process – one that has remained heavily weighted towards physical models[16]. By cycling between physical and digital models, Gehry has been able to continue his design process with very little compromise. One of the most significant benefits that Gehry cites is that the computer can provide instant cost estimates during the course of design. He talks about how this aspect of the computer has affected his design:

Consequently, I'm designing with specific conditions and I don't go out of bounds. Because, you know, when you design without knowing the boundaries, you find a form and you become enamored with it. It crystallizes. It's a fixed image. Its really hard once it's a fixed image to go back and cut, cut, cut. But if you are cutting as you go, you don't get fixed until you know you can do it. When you're fixed, you're fixed. You know you can afford it. [17]

Equipped with this powerful new tool, Gehry has regained the central position similar to that of the medieval master mason. Though the systems of construction are exponentially more complex that a monolithic stone building, the computer model contains the knowledge of the entire construction. There are several ways the information can be used. For example, data points can be taken at any section line, profile lines generated, or skin material tensions calculated. Each of the primary trades can use the information embedded in the model. Just as the master mason was the person who understood every corner of the building and how it was to be constructed, the architect who creates the model can find information about any part or section of the building. Gehry specifically recalls the master builder in several interviews, in this one about the Guggenheim Bilbao he states:

We found early in our exploration of developing relations with builders that the more precise the delineation, the more it could be demystified and reduced to the ordering of materials of a certain shape and almost the ability for the contractor to paint by the numbers. It gave the contractor security in their bid and prevented inordinate premiums. Of course it was more expensive, but not outrageously so. It is this new process that was tried on a large scale in Bilbao. It has resulted in a completed building within a reasonable budget and within a reasonable space of time. What it all leads to, is the architect eventually taking more responsibility and becoming once more the master builder. [18]

The gains that Gehry describes are mostly in the realm of bidding and pricing of the work. There are other equally powerful ways that the computer model is employed to make his forms "buildable". I propose that the computer model is a reincarnation of the medieval mason's template. It is a source of information controlled by its designer, encoded with all the information necessary to construct the building forms.

THE SOURCE OF MASTERY

Had they entrusted their power to the instruments necessary to construct form and space instead of the legal instrument of the contract, modern day architects might have maintained the absolute power of the medieval master mason. Full-scale drawings, models or templates have held an important role in construction throughout history. The medieval master builders also used full scale templates as a means of design and communication to the fabricating mason. Floor tracings of gothic cathedrals have survived, testament to the working processes of the time. The historian Lon Shelby describes the preeminence of the template over any of the drawings, full-scale or otherwise:

...masons' templates, rather than architectural drawings, were the primary instrument by means of which mediaeval architects – that is master masons – transmitted their architectural forms to the masons who executed the forms in stone. [19]

Templates from this era were often generated by a systemmatic formal manipulation of geometry and proportional ratios. The generative calculations for the templates was sometimes recorded on the templates themselves allowing the users to modify the templates to other scales. The two dimensional template would contain information to create secondary templates and eventually, the three dimensional stone.

In France during the late seventeenth century, the stereotomic device called a "trait" was used to enable precisely defined stonecutting. As a layout drawing, the trait was often beautiful on its own terms, but it was created for the purpose of guiding the mason. As Robin Evans tells us in his chapter "Drawn Stone", after the trait was complete,

> *from here it is a short step to the mason's yard. because each face. when drawn full size. would become a template furnished to the mason as a paper. board or zinc panel.*
>
> *Each stone of the* trompe *therefore has its individual and unique specification. They are cut and dressed as prefabricated items. which. when assembled on site. magically combine into perfectly unified form.* [20]

The trait was a development of the medieval template, more sophisticated in appearance but equal in power to the template.

In late nineteenth century America, when the architect's power to affect construction was already eroded by contractual prescribed roles, documentation of the building's forms were of paramount import. Davis discusses the kinds of drawing involved in documenting a large building of the time:

> *The New York firm McKim Mead and White for example. which some scholars consider the prototype of the modern architectural firm. attempted to maintain complete control over all aspects of the building's design. materials and production. This control was maintained through the mechanism of drawings. in which little was left to the discretion of the craftsmen. For the construction of...prominent buildings...drawings were made at three different scales. done at different points in the construction of the building: 1/4" drawings for the bidding and the overall layout: 3/4" drawing for such operations as the exact placing of the stones and openings in the exterior walls: and full-scale drawings for giving instructions to the craftsmen who were making details such as cornices. window trim. and interior plasterwork.*
>
> *...Many of the[se full scale] detail drawings...did not have the precision of the final work. with all the critical dimensions called out...Even though the architect made the sketch. the craftsmen were still responsible for giving precision to the design. subject to the architect's approval....Finally in the twentieth century. the full-scale details have largely disappeared from the architect's responsibility....* [21]

In this same era, the innovative structural design of the Auditorium Building in Chicago challenged Adler and Sullivan to come up with more specific ways to communicate the design in the field. Differing from McKim Mead and White's use of drawings to document every known aspect of the building, Adler relied on three-dimensional tests to discover what he might not have known before. In her article on the artifacts produced during Adler and Sullivan's work, Clare Cardinal-Pett writes:

> *Throughout the design and construction of the Auditorium Building. drawing was frequently abandoned in favor of alternative means of modeling: full-sized samples. mathematical calculations. and ingenious on-site testing devised by Adler and his array of consultants. These design methods have more in common with the everyday practices of the English. who were slow relinquish the craft-based approach of medieval engineers and designers...diagrams. templates and prototypes were made with materials and methods of construction in mind – often on the site or at the factory as part of the on-going fabrication process.* [22]

Gehry's computer model is the equivalent of Adler's resourceful inventions. For all their formidable quantites of data, Gehry's digital models are surprisingly crude. These are not seductive presentation images, but working tools developed with realities of the construction or fabrication site in mind. Curiously, the CATIA model has supplanted the two-dimensional drawings in Gehry's office. There is an eerie emptiness to the working drawings. Each time one looks for critical dimensional information there is a note which appears over and over: "See CATIA model for information"

In addition to controlling costs during the design and ensuring that the bids are reasonable, the accuracy of the computer model makes it an ideal base for the manufacturing process. The computer model can provide dimensions taken from any point, material take-offs for skin and structure. Viewing the model becomes a way to envision how the elements will be put together, exposing conflicts in the construction sequence or between systems. Used in this way, the computer model is very similar to the full scale drawing or mockup that the master builders employed. As information about structural members, cladding, sprinklers and ducts are added, the model becomes a three dimensional record of "as-built" conditions.

Examples of all of the computer-enabled gains in design and construction control are illustrated in the Experience Music Project (EMP). While Gehry's Guggenheim Museum in Bilbao garnered hyperbolic accolades from the architectural press, the flashy forms, colors, contents and budget of EMP has captured the public's attention. In addition to demonstrating some of the most complex forms in Gehry's exuberant language, EMP has a ground-breaking structural strategy. As an illustration of the model as master mason's template, EMP provides an ideal case study. [23]

EMP had one of the highest budgets among Gehry's projects to date. There were few cost-driven cut backs in the forms. At every juncture the project grew more "swoopy"; compound curves folded into themselves, fluid elements appeared on both the exterior and interior. To achieve these forms, a new technological advance was tested in EMP. In previous Gehry projects, the curved forms were created primarily with straight structural framing elements. In EMP, the structural framing members were curved to follow the approximate forms of the final building. Wide flange members were created by cutting curved web pieces and welding flange pieces onto them. The cutting of the web was achieved through CAD/CAM software that could translate the CATIA model information to a plasma cutter. The flanges were roughly bent to the final curves, then a robotic welder was developed that could ride along the web and continuously fuse the pieces together.

The skin of the building did not follow the curved structural beams exactly. A network of steel pipe provided a secondary structure for the skin panels or groups of panels to attach to[24].

Fig. 1. EMP under construction.

The cladding manufacturer was also heavily reliant on the CATIA model as the basis for his manufacturing. Similar to the structural steel process, the data provided by the architect's computer model drove the CAD/CAM process[25].

The CATIA model could be used to generate an infinite number of full-sized templates. When the construction was relatively straightforward, CATIA information could be directly applied. To create the interior curved plywood wall, known as the snake wall, the CATIA model was sliced at successive levels both horizontally and vertically. Each slice became a full-sized template for one of the plywood ribs. Through an egg-crate construction, the plywood ribs could be fitted together to form the curve defined by the model.

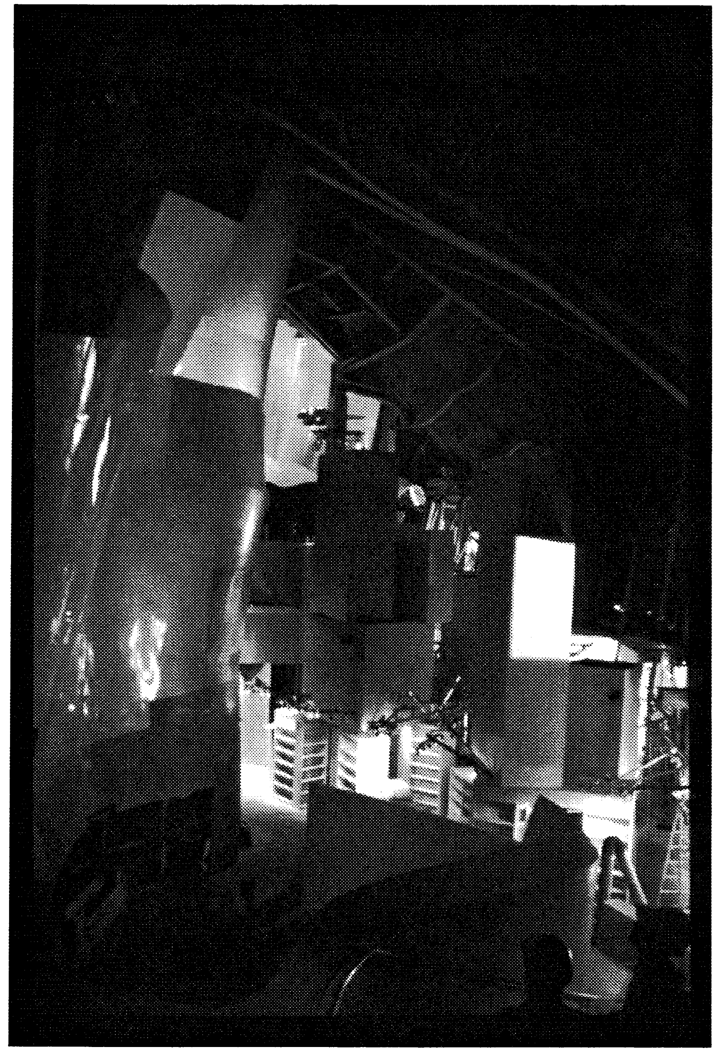

Fig. 2. EMP lobby interior showing finished snake wall.

CONCLUSION

Gehry's high-tech computer model is remarkably similar to ancient devices used to describe building form. Through the application of cutting edge technology, Gehry has re-discovered the power once held by the master mason of the medieval era. Reasserting his control over the information that describes the forms, Gehry has found a way to circumvent the usual restrictions placed on modern architects. The CATIA model is a multi-phase tool, useful in the design, bid and production of design. It is far more effective in delivering the power to control construction than the most well-written contract could ever be.

As the technology becomes available to architects of more modest resources, CATIA and software like it have the possibility of transforming practice. It is not only the large firms with large-scale projects who will drive innovation in the profession. Firms such as SHoP in New York have effectively used computer models to generate construction templates for small-scale installations made of cedar or metal. At these smaller scales, it is easy to see the computer model as a full scale virtual model that is only a short step away from the fabrication floor.

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NOTES

[1]Vitruvius, preface to *Ten Books of Architecture*

[2]Nicholas Hiscock in his book *The Wise Master Builder*, Brookfield Vt: Ashgate Pub., 2000 p. 171 quotes from a 13th century text written by Nicholas of Biard: "In these great buildings it is the custom to have a chief master who only directs things by word, seldom or never lays hand on the work himself…."

[3]Coleman, Roger, *The Art of Work*, London: Pluto Press 1988, p. 17

[4]Fitchen, John. *The Construction of the Gothic Cathedrals*, Chicago: Univ. of Chicago Press, 1961, p. 3

[5]Hiscock, Nicholas. The Wise Master Builder, Brookfield, VT: Ashgate Publishing, 2000, p186-7

[6]Fitchen, op.cit., p. 5

[7]Wright, Frank Lloyd. "The Art and Craft of the Machine", from *An Autobiography* (1932) reprinted in Frank Lloyd Wright, Writings and Buildings, ed. Kaufman and Raeburn, New York: Signet, 1960, p. 57

[8]Davis, op.cit., p 122

[9]Davis, Howard. *The Culture of Building*, New York: Oxford Univ. Press, 1999, p. 196-7

[10]Davis, op.cit., p. 196

[11]4.2.3 AIA Document A201 General Conditions of the Contract for Construction (1987)

[12]Moneo, Rafael. "The Solitude of Buildings", Kenzo Tange lecture, Harvard University, March 1985

[13]Piano, Renzo, "Have an Idea, Act as an Architect" in *Japan Architect*, vol 1. 1994

[14]Gehry, Frank, "Commentary" in *Gehry Talks*, ed. Friedman, New York: Rizzoli, 1999, p. 55

[15]Gehry, Frank, "Commentary" op.cit, p. 54

[16]This process has been well described by both Coosjie Van Bruggen in *Guggenheim Museum Bilbao*, New York: Solomon R. Guggenheim Foundation, 1999 and Mildred Friedman in *Gehry Talks*, New York: Rizzoli, 1999

[17]Gehry, Frank. "Commentary" op.cit., p.52

[18]Frank Gehry as quoted in Van Bruggen, Coosje. *Guggenheim Museum Bilbao*. New York: Solomon R. Guggenheim Foundation, 1999, p. 138

[19]Shelby, Lon. "Mediaeval Masons' Templates", *Journal of the Society of Architectural Historians*, May 1971,p, 142

[20]Evans, Robin, *The Projective Cast : Architecture and Its Three Geometries*. Cambridge: MIT Press, 1995, p. 189

[21]Davis, op.cit., p. 196

[22]Cardinal-Pett, Clare. "Necessary Excess", *Journal of Architectural Education*, 51/1 (Sept 1997), p. 52

[23]I will focus on the use of the model in construction and fabrication. The design process for EMP was a typical one for the office and CATIA was used in a manner similar to the one described by Coosje Van Bruggen for the Guggenheim Bilbao.

[24]Paul Zumwalt, the client representative for EMP told me that the steel was such a success that he wished that they had pushed the limits of the process further and simplified the skin. The variation in distance between the structure and skin caused many problems in the construction.

[25]There was not a direct path from model to manufacture, both the steel and the cladding manufacturer had to submit shop drawings that were tediously checked against the model. In the case of the cladding, the manufacturer, Zahner, used another software which was compatible with CATIA called Pro-Engineer to drive their CAD/CAM system.