Structure-Skin Interface:
An Interactive Approach Using Advanced Media

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INTRODUCTION

The architectural interaction of a building's structure and its skin has enormous possibilities — creative approaches to the design and relationship of building structure to its skin can result in dramatically expressive and appealing design. The structure/skin interface can also lead to unique design solutions, which make building construction and performance more efficient and cost effective. Innovative structure and skin design can also be used to develop buildings in which skin, structure and building services are combined in such a way as to reinforce and improve the individual performance of each building subsystem.

In some building systems, including stone, concrete, brick and air supported fabric structures, structure and skin can be inseparable. But for most buildings using modern materials (timber, steel glass, etc.) the design and construction process increasingly treat structure and facade as separate elements — the building skin is merely a cosmetic aspect of design, which hangs from a separately conceived and designed structure. As Hugh Dutton has noted:

> *" Engineers design structure and architects design curtain walls. This professional definition is repeated on site, where structural trades (concrete, steel, etc.) and cladding trades (glass, aluminum cladding, etc.) work in their discrete territories. The building industry is organized around theses distinctions between professional trades to the extent that everyone involved with a typical project assumes that the standard procedures will hold: structure is employed for the single purpose of supporting the building, while the cladding is an envelope around the structure to keep the rain out."*[1]

These conceptual and professional divisions are also reflected and reinforced in the academy. In architecture programs, building structural behavior is taught through the structures curriculum, and the design of building skins is taught largely separately within the construction technology sequence of courses. The structures curricula and building technology sequence are distinctly separated both in content and teaching methodology. Most construction technology courses are based on qualitative methods that facilitate an understanding of building components, building envelope, and their assemblage. On the other hand, structures courses tend to be focused on the analytical aspect of building construction and concentrate on individual building member analysis and design. Even the faculty teaching these sequences come from different academic backgrounds. Most construction technology courses are taught by full time architecture faculty who are actively involved in teaching design studios or adjunct faculty who are practicing architects. Most structures courses are taught by engineers.

The problem is that the intersection of building skin and structure is where many lessons can be learned, and where entirely new possibilities for both dramatically expressive and efficient building design can be achieved. It can easily be argued that most architecturally significant buildings are those which synthesize structure and the building envelope in unique manner. Something is lost when they are separated — social and cultural losses in the form of unimaginative and repetitively designed buildings, and real economic losses created by inefficiently performing buildings. The education of the architect, and therefore the professional practice of architecture, also suffers from an ongoing lack of integration between these two areas of study. The creative use of technology and structural expression is only rarely taught in the design studio. Architecture students spent most of their time in formal explorations rather than thinking about innovative solutions for resolving technical problems of practical design. By excluding, or not specifically addressing issues of structure and building construction within the design studio, students are poorly served in that a primary opportunity to reinforce these concepts are lost, the central importance of structure as a design element (and opportunity) is overlooked, and new opportunities for students to develop different and innovative building design are wasted.

Recent developments in computer technology, in particular, advanced multi-media computer modeling and animation software, can be used effectively in the architecture curriculum to overcome some of these traditional professional biases. Combined with simple curriculum changes, advanced digital media can be an effective teaching tool to integrate or dissolve the structure/skin boundary, can very effectively be used to teach structures in ways more amenable to the proclivities and skills of the architecture student, and provide a means for a more meaningful exploration of the relationship and possibilities of building structure and skin.

DIGITAL MODELING AS AN EDUCATIONAL TOOL

A considerable portion of architectural education is based on studying the work of significant architects and important architectural works. Learning through example is crucial to architectural instruction, but effectively teaching architecture students structures and construction technology is limited by three main factors. First, the structures curriculum, teaching methods and instructional tools are borrowed wholesale from engineering programs with little modification. Instruction is therefore highly quantitative, communicating even basic concepts using a high-level mathematics nomenclature. Architecture students have neither the background, disposition, nor time to master the mathematics skills required to understand or utilize a system based on highly abstract mathematical models and therefore quickly become uninterested, frustrated or intimidated by the structures curriculum.

Second, the applied-engineering approaches to teaching structures uses a methodology which consecutively dismantles a structure into extremely small sub-components, focusing on a particular element, detaching it from all other connected structural members, and then reducing it to a system of arcane symbols and mathematical formulae. As a conceptual and instructional system, structural analysis of this kind almost never attempts to connect detailed analysis back to broader building design and construction principles.

Third, the examination of architectural case studies is limited by traditional two-dimensional photographs and drawings. Most often the study of great works of architecture is limited to viewing a few static images or graphical representations of a building's structural and non-structural components followed by quantitative analysis of its behavior.

Alternatively, using advanced digital technology and computer modeling can offer many advantages and enhance teaching effectiveness tremendously. First, by using a computer-generated model, a building can be studied interactively rather than statically. Providing the possibility of moving through a building and exposing structural elements, cladding elements, connections and details of how various components of buildings meet by deliberate selection, engage the building in its entire context. Using computer-generated models can produce digital environments, which can be manipulated to emphasize or de-emphasize certain aspects of a building, used to expose conditions that are impossible to view through the building skin, to select specific viewpoints, and magnify a detail condition for visual investigation.

Using digital environments also permits the investigation of many layers of information simultaneously. A user can engage in the study of a particular element in a smaller window, while the larger context is still in view, grounding the investigation. A dynamic computer model, properly developed, can be a means to conceptualize technological knowledge in a total building system-context.

Lastly, building performance can be demonstrated using animation visually and directly, rather than as abstract mathematical formulae or crude schematic representations. This visual approach to instruction is critical for most architecture students, providing instruction, which better meets the architecture student's needs and capabilities and measurably improves the understanding and application of basic and advanced structural engineering and building construction principles. Quantitative scientific methods can be effectively combined with qualitative and conceptual methods, grounding both in the practical aspects of building design.

Using advanced computer modeling and animation software, a small research team at the state University of New York at Buffalo has developed a prototype instructional software package — the *Integrated Structures Instructional Package* (ISIP) — which is now being used as the core instructional tool for the structures program, and is being revised to teach both structures and construction technology concepts within the architecture curriculum. Combined with instructional changes in the design studios and the development of inter-department instruction between the architecture and engineering programs, the University is pioneering new ways of delivering structures, construction technology and engineering instruction.

The use of interactive digital instructional tools is central to these programmatic changes. Modeling, showcasing and studying great works of innovative architecture using the instructional software is now being used to great effect. The following case studies, all part of the instructional software, that demonstrates how the software functions to help bridge the structures/building technology gap, significantly improve structures and construction technology instruction, and demonstrate the best and most innovative building design practice.

CASE STUDIES

Integrated structure and skin: The Waterloo International Terminal

The Waterloo high-speed train station is a great demonstration of a successful integration of structure and skin. The innovative use of structure and cladding at the Waterloo Terminal creates an extremely flexible system, which allows for movement of the skin in response to the changes in structural loading conditions. The train station is essentially a large roof shed, which covers five train tracks extending over 400 meters. To design the project the Architects, Nicholas Grimshaw and Partners had to work with extremely complicated site conditions such as twisting track rails, existing underground tunnels and a proposal for an overhead building.

The Architects' proposal, which completed construction in 1993, is a structural system composed of a series of asymmetrical three-hinged bowstring arches tailored to fit the site and accommodate clearance for train traffic. The asymmetrical geometry of the bowstring arches is a direct response to the odd number of tracks. In one side of the building roof rises with a gentle curve, while in the opposite side the roof clears the trains with a sharp rising slope. To provide the required strength each bowstring arch is composed of trussed elements, which become very deep at central locations. The deep truss elements create a problem in the shallow end of the arch. To resolve this problem the structure reverses its direction. On the shallow side of the structure the truss members are placed outside the building envelope to provide clear space for train passage and on the deep side the trusses are located inside adding volume and interest to the interior space.

In a large scale building like the Waterloo Terminal the design of structural details and connecting elements can become an overwhelming task. The number of connections and the various members coming to connect at common joints could produce bulky and visually intrusive connections. In some truss members the connections had to be designed to receive loading from a six or seven directions. To simplify some of the connections, the steel frame was cast to receive the connecting members, eliminating the need for additional connecting elements.

The Terminal has been modeled and included in the ISIP as a case study demonstrating the possibilities for integrating structure and skin to produce effective and graceful architecture. It is particularly interesting to study in that it applies a particularly striking architecture to a typically mundane piece of transportation infrastructure.

Fig. 1 is an image of a computer-generated model of the train station, which provides a few options in exploring some of the innovative features of the structure, including the geometry, behavior of the typical three-hinged arch under gravity load, and connections. By clicking any place on the image a close up view of that location will be presented. For example, if any of the connections are selected, the upper left window will be adjusted to show the selected view. If the viewer selects the connection of the arch to its base, the upper left window will zoom in the pin connection of the arch base. Selecting the window on the right hand side will play an animation showing the assemblage of the connection. Fig. 2 shows two frames of this animation. By selecting the arch element presented in the lower left window, the load distribution pattern of the arch will be demonstrated. Fig. 3 has two frames of the animation showing the load travel path through the arch.

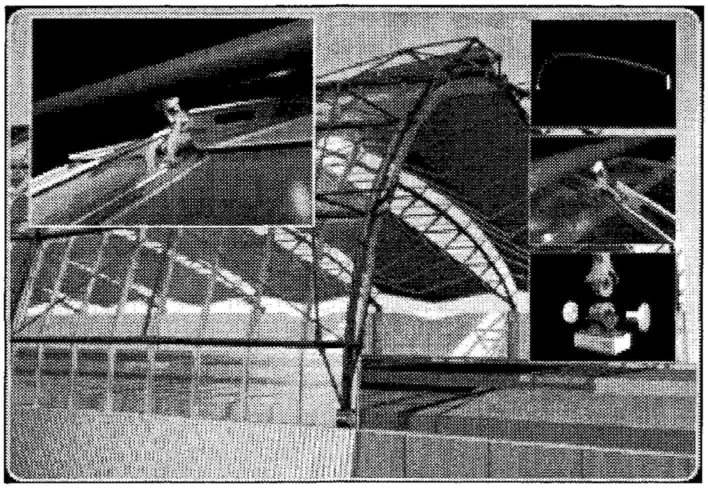
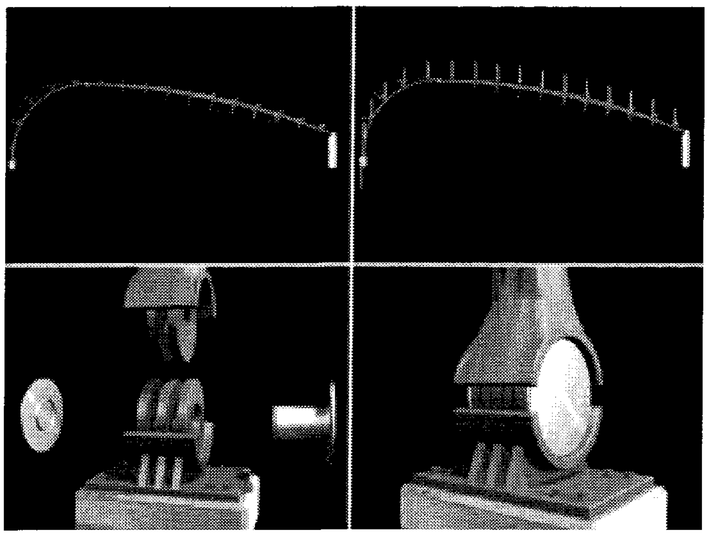


Fig. 1: Overall view



Figs. 2 & 3: Animation frames

The focus of technological innovation in the Waterloo train station is the shed cladding. The cladding system is composed of glass and matt finished stainless steel. In order to accommodate the irregular geometry of the site and structure standard rectangular glass sheets that would overlap each other rather than fitting the structure are used. Grimshaw explains:

> *"The twisting nature of the structure would have made a standard glazing system extraordinarily expensive, involving thousands of different sizes and shaped components. To overcome this a loose-fit approach was adopted, in which a number of different sized panes are used, each held in its own frame, and overlapping at the top and bottom like roof tiles."*[2]

Another critical consideration in the selection of cladding scheme was the effect of impact load produced by rapid movement of the high-speed trains. The cladding glass had to accommodate deflections of up to 6 mm[3] caused by the train movement.

Fig. 4 shows three frames of an animation that explains the detailing and assemblage mechanism of the glazing system. This system is composed of a pair of stainless steel rotating arms attached to the glass and the stainless steel frame. " the gaps between the glasses are vertically sealed with an accordion style gasket and horizontally by a wiper blade. Together these seals allow standard square panes of glass to be fitted to the varied steel geometry like the skin of a snake of an armadillo"[4]. The animation begins with an exploded axonometric of the assembly, showing how the system fits and moves with the impact loads. The last frame of the animation is a labeled image showing the various components.

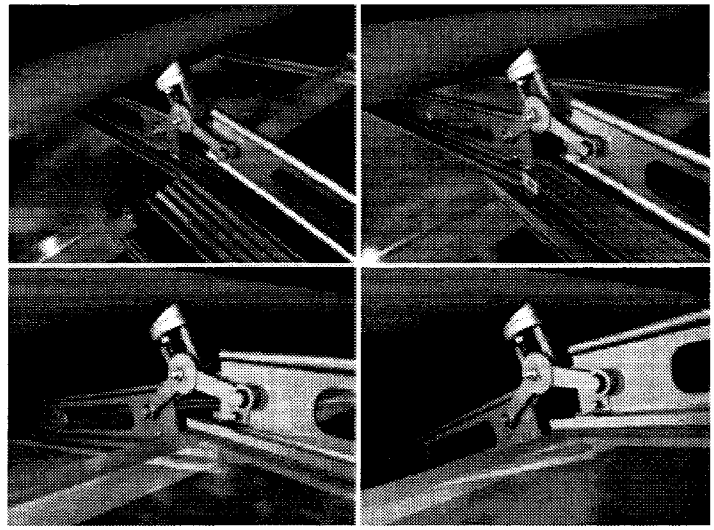


Fig. 4: Animation frames

Structural expression with a fitted skin: *The Hong Kong Bank*

The Hong Kong Bank is one of the best examples of a highly innovative building system, using a minimalist approach to create a structure that is visually reflected in both the interior and exterior of the building. The function of the skin is to fit the structure almost without any presence.

Designed by Norman Foster and Associates the Hong Kong Bank was competed in 1985. Among many important design considerations was an efficient structure achieved by the use of minimal material, open and flexible interior space and a relatively large proportion of usable space. In a lecture at Pompidou Centre in 1981, Norman Foster stated that "the structure of our building is quite different from the usual office tower in Hong Kong. It is steel, which is one fifth of the bulk of concrete; it has a wide span and achieves an unusually high percentage of usable space, along with a number of other befits."[5]

The building is 179 meters tall, with a foundation system 34 meters below ground level. There are 42 stories with the largest floor area of 3,215 m^2. The structure has 27,000 tons of structural steel, 3,500 tons of aluminum cladding, 35,000 cubic meters of concrete and 32,000 m^2 of glass area.[6] The building structural system is composed of eight massive masts, which are placed in two parallel rows. Each mast consists of four tubular columns connected with hunched horizontal beams. To provide a clear space totally free of columns and allowing full flexibility for layout of the interior spaces, the floors of the building are hung from a series of hangers connected to suspension trusses. The vertical masts and the horizontal suspension system act very similar to a bridge structure. The weight of the stacked floors are picked up by hangers and transferred to trusses at five locations. The load is then transferred to the masts and brought down to the foundation.

The structural functions can be clearly explained by using the ISIP. Fig. 5 is an image showing a picture of the structural model and a number of different views of the building. When any part of the structural model is clicked on, the image in the window changes and presents information that only pertains to the specific selected part. For example, Fig. 6 is a single frame of an animation that shows how the entire structure works under gravity loading. The weight of the stacked floors are represented by arrows, which follow the hanger elements connected to the floors at the mid span traveling to the top truss, redirected to the masts, and then to the foundation system.

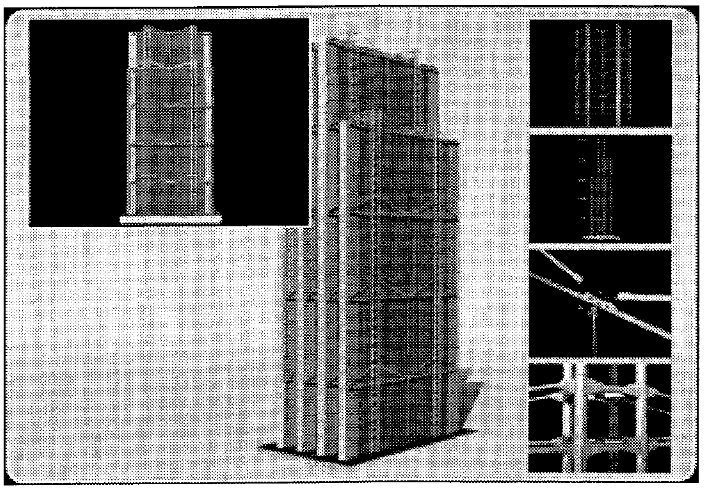
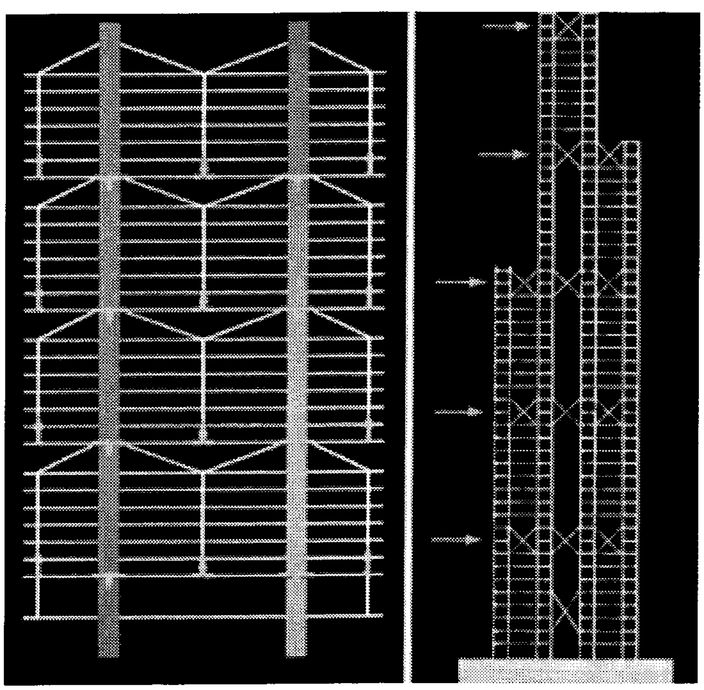


Fig. 5: Overall view

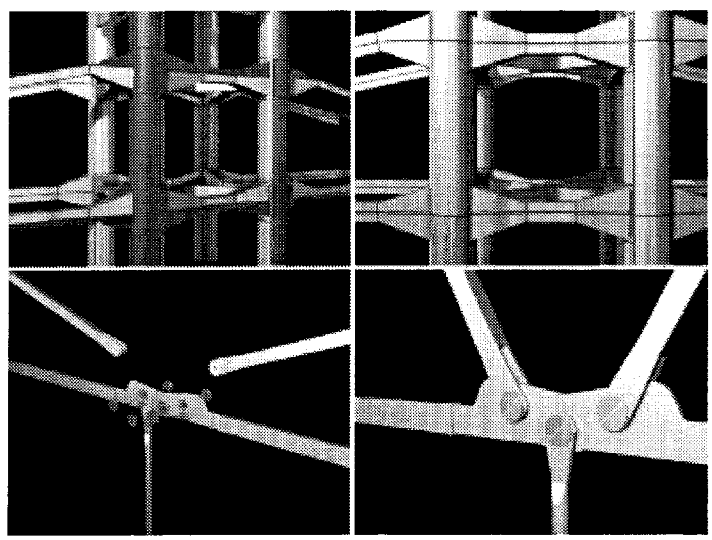
The lateral stability for the building is provided by two to three-story cross braces, which connect the masts internally and create stability in the north-south direction, where the structure is most vulnerable to earthquake and typhoon loads. Fig. 7 is a single frame of an animation demonstrating the structural behavior in response to lateral loads.



Figs. 6 & 7: Loading diagrams

Design of such a large-scale building presented many challenges in construction details. One of the important issues regarding the design of major connections such as the suspension truss system was that loads could reverse their direction at any time and produce unacceptable movement of the structure. The solution that was adopted was a creative use of a standard peg device that is used in large machinery.[7] This type of connection allowed for compensation and some miss-alignment of the pin while still allowing a tight fit. To present this connection detail and its assemblage the computer generated model will produce a close up view of the connection detail of the suspension truss followed by an animation showing how the connection is put into place. Fig. 8 shows three frames from this animation.

As discussed previously the visual expression of the structure was an important consideration for the architect. This had a tremendous effect on the selection of possible cladding schemes. Two options were considered closely.The first option was to expose the structural framing on the outside of the building in which case weathering steel would be used. In this case structure would have a pure expression without interference of the cladding material. The implementation of this option had many significant technical difficulties and it was not accepted as a possible solution. The other option, which was eventually adapted for the entire structure was to use aluminum cladding that would fit the structure without any significant impact or change to its visual expression. Stephanie Williams explains the cladding scheme as the follows: "because of the desire for precise architectural expression of the steel structure, the cladding was designed to fit the structure like a glove. Each module would have to fit into a precise space a precise location, and connected to the structure with predetermined fixing points."[8]



Figs. 8 & 9: Animation frames

Fig. 9 shows three frames of an animation that demonstrate the construction of a typical section of the mast cladding. This animation is played when the user clicks on any part of the mast element on the overall picture of the model. The first frame is a deconstructed view of the mast and the cladding, exposing all the protective elements fitted in between the structure and the cladding. This includes the thin cement based coating used for corrosion protection, the ceramic fiber blanket fixed to a stainless-steel mesh, reinforced aluminum foil and the 6 mm-thick aluminum sheet cladding[9] all labeled for clarification. The last two frames of the animation show the assemblage of the cladding.

Separation of structure and skin: *The Patcenter*

The Patcenter is a research facility located on the outskirts of Princeton in New Jersey. The building was designed by Richard Rogers and Associates and completed construction in 1985. The building functions as a research center and the related support activities required planning of large open spaces with great flexibility. The Architects' response to the building program was to use a suspended tension structure that made it possible to make large spaces without interruption of frequent vertical supporting elements. The major vertical support system for the entire structure is a series of nine masts placed in a long row organizing a central circulation spine. Each mast consists of two inclined compression members supported by a portal frame. These masts support the single story wings, which house the various functions of the building. The horizontal spanning system for supporting the roof is composed of floor beams that collect the loads and transfer them to the stringers, which are supported at the mid span by the tension cable connected to the masts.

Fig. 10 shows an overall view of the structure with a series of windows on the right side. Selecting the lower left window will play the load distribution path for the entire structure. Fig. 11 shows three frames of this animation. The animation proceeds by loading the structure with arrows that represent the roof loading. The force arrows move to the floor beams, then to the stringers, traveling up the cable members and then redirecting toward the foundation when approaching the mast.

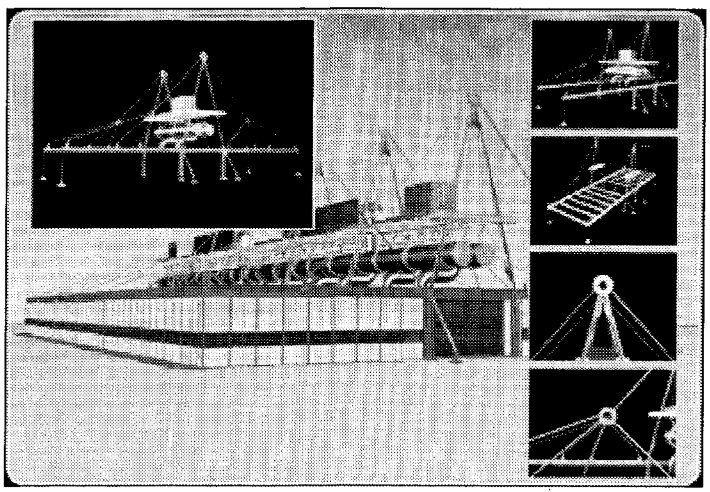


Fig. 10: Overall view

An interesting and innovative feature of the building is the integration of the building services into the structural system for providing lateral stability of the masts. The concept of a mast structure with a central circulation space provided the ideal location for placing the building services. All the building services are either located at the ground floor next to the spine or at roof level above the spine. The roof level services are connected to steel platforms, which are suspended from the central masts. Although service loads place additional gravity load on the masts, they provide lateral stability by connecting the masts and leveraging the weight to stop movement in the horizontal direction. Ian Gardner explains the interaction of masts and the service components as the following:

> *"out of plain loading on the masts and suspension system are transmitted down to the main roof level via the structural chassis of the service platforms. All horizontal forces associated with the vertical support systems are the resolved at the roof level and transferred to the ground level through the combination of central portals and diagonal bracing at the end and the sides of the building."* [10]

The computer-generated model can explain interaction of the mast and the service platform clearly. By clicking on any part of the service elements on the image shown in Figure 11, a close up view of the service and the mast is provided as shown in Fig. 12. Further clicking will show how the service load is transferred in both vertical and horizontal direction. Another successful feature the structural scheme of the Patcenter is the highly visible prefabricated connections that stress the presence of its structure.

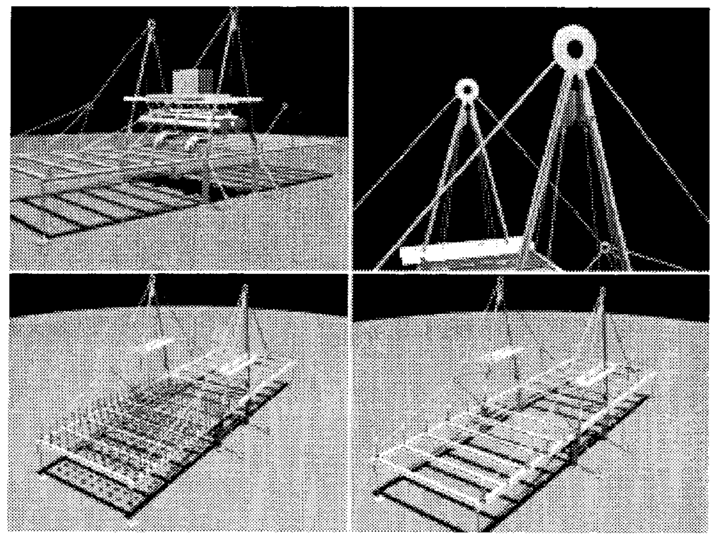


Fig. 11 & 12: Detail view and loading diagram

The important consideration with respect to the selection of cladding was to allow maximum light through the glazing but eliminate the glare that would produce undesirable contrast levels. After a series of studies a Kalwall translucent cladding was selected.

> *"This proprietary system comprises a sandwich panel formed by bonding two specially formulated, light transmitting, fiberglass sheets to either side of an interlocked aluminum grid frame. For maximum light transmission the gap between the sheets is left empty. To increase the thermal insulation the gap is filled with special inserts of translucent fiberglass."* [11]

The construction and assembly of the cladding system can be explored using the computer-generated model. The cladding can be selected by clicking any place on the wall element (see fig. 10). Further clicking will bring a detail section of the cladding explaining its construction and assembly using animation and annotated images.

CLOSING REMARKS

The possibilities for using digital modeling to effectively investigate critical aspects of architectural design precedent study is only at its beginning stages. While digital technology is by no means a panacea for the difficulties in studying and teaching aspects of the structure-skin interface, it can be demonstrably effective teaching tool. Used creatively, the practical, technical and innovative aspects of structural and cladding design can be communicated simultaneously.

Further work on the software system is aimed at expanding the library of architectural case studies and improving the interactive characteristics of the system even more. The use of these tools also embodies an important instructional objective, seeking to improve basic technical understanding, but recognizing that Schools of Architecture are also responsible for producing new architects capable and inspired to continuously improve the professional practice of architecture and advance *both* the aesthetics and performance of new building technology.

NOTES AND REFERENCES

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[2]Marcus Binney Architecture of Rail: The Way Ahead, (London: Academy Editions, 1995, p.13)

[3]See Rowan Moore, Structure, Space and Skin: The work Nicholas Grimshaw and Partners, (London: Phadion Press limited, 1993, p.41)

[4]Marcus Binney, Architecture of Rail: The way Ahead, (London: Academy Editions, 1995, p.13)

[5]Ian Lambot, Norman Foster and Associates Buildings and Projects, (Hong Kong: Watermark Publications, 1989. p. 118)

[6]See Tao Ho, "A Re-evaluation of Tall Buildings", Process Architecture (1986), no.70, p.50

[7]See Ian Lambot, Norman Foster and Associates Buildings and Projects, (Hong Kong: .00000.Watermark Publications, 1989, p. 219)

[8]Stephanie Williams, Hong Kong Bank: The Building of Norman Fosters's Masterpiece, (Boston: Little, Brown and Company, 1989, p.148)

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[10]Ian Gardner, "Patcenter", Arup Journal Summer (1986), V.21, no.2, P.8-16

[11]ibid