Steel: Fun is in the Details!

Developing expertise to support a tectonic culture

versus "God is in the Details"
Ludwig Mies van der Rohe
On restraint in design, NY Herald Tribune 28 Jun 59

INTRODUCTION:

The developing tectonic culture of architecture, as expressed in the material use of steel in design and construction, would certainly beg to differ with the restrained views of Ludwig Mies van der Rohe in his oft quoted phrase. The restrained modernist expression of steel in architecture has given way to a bold new set of manifestations that have chosen steel as their material of choice. Both "standard steel shapes" and "steel tubes" or HSS sections are being employed to create the architectural expression of the building. Such expression could be seen to be rooted in the iron architecture of the mid 19th century, which was subsequently elevated to become part of a High-Tech style that resurged during the 1970s with buildings such as the Pompidou Center by Piano and Rogers. Current trends in exposed steel use might be culturally different from the motivation behind High-Tech style, but similarly requires that the designer have a high level of expertise in the development of connection details.

Figures 1 and 2: Two views of Baltimore, Maryland. Exposed steel in a 19th century railway station versus the structure of early modern and modern skyscrapers

AISC, in its article on Architecturally Exposed Structural Steel Construction, May 2003[1], cites the roots of the current trend of exposed steel and transparency in design to the Chicago O'Hare United Airlines Terminal designed by Helmut Jahn between 1985 and 1988[2]. Indeed, airport architecture has succeeded in pushing the use of exposed steel to incredible heights. Transportation related architecture and engineering has historically been the building typology that has succeeded in pushing both the structural and design limits of materials. Railway architecture played this role in the 1800s, in the creation of the expansive airy stations that were constructed first in Europe, then North America. Such buildings had large span and height requirements whose sole solution lay in iron and steel construction. The role of railway stations as "connectors" in the urban landscape, also assisted in disseminating ideas of structure and construction to new places, as the hundreds of thousands of travelers passed through these magnificent, inspirational buildings. Such has become the current role of airport architecture.

Whereas the use of a fully exposed steel structure may not be allowed by the building and fire code for certain occupancies, airline terminal buildings do permit such exposure, and this, combined with requirements for extremely large column free spaces, have pushed the exploitation of the structural characteristics of steel – in particular, steel tube assemblies. Steel tubes, when used in a three dimensional truss-like fashion, have statistically been proven to succeed in creating a lighter structure which can more graciously span across large distances, when compared to conventional steel or concrete construction.

Figures 3 and 4: Interior detail and view of Chicago O'Hare United Airlines Terminal showing the use of architecturally exposed steel structure and high level of transparency.

This is not to say in reference to the final design for O'Hare (picture above) that the steel solution chosen is has placed budget or economy at the top of its requirements list. The 4-HSS tube column could have been accomplished with less detail and fabrication cost were it designed in an alternate fashion or with an alternate material, like concrete. It is to say that the expression chosen made for a far more interesting extended sojourn at this airport during the Eastern blackout of August 2003!

THE LANGUAGE OF CONNECTIONS AS AN EDUCATION TOOL:

In its exposed state, and addressing the simultaneous dual roles of structure and architectural expression, steel design can be seen as an excellent teaching tool for students of architecture. Exposure makes the tectonic development of the material accessible for learning. Architecturally Exposed Structural Steel (AESS), as it is currently specified, also requires a deeper understanding of fabrication and construction/assembly methods as the drive to achieve ultimate artistic quality in the final instance, can create unnecessary cost overruns if accompanied by unrealistic expectations.

The basic understanding of steel construction lies in its roots as an "assembled", largely prefabricated methodology. Steel construction is "elemental" in nature, and its artistry reliant on not only the appropriate choice of members (shapes versus tubes), but also heavily in the method of attachment. AESS steel design requires detailing that can approach "industrial design standards" when creating joints between members. The structural requirements of shear and moment resistance must be accommodated, in addition to "other" considerations such as balance, form, symmetry and economy. If the creation of connections requires an excessive degree of unique fabrication details, the designer can price the project out of existence.

Except in the instance of precast concrete joinery, which is normally dependent on hidden steel to create its hinge connections, the normal commercial use of systems such as reinforced concrete hide much of the connection detail within a moment based system of connections where issues become fluid and obscured. As a teaching tool, this makes it more difficult to understand the actual requirements of the connections in handling load transfer, as well as construction and fabrication detailing.

Connection Types:

Steel design rests largely in the understanding and creation of connection types. Without such basic structural knowledge it is not possible to conceive of let alone properly design a steel building, particularly one that might choose to openly express the steel system. Advanced detailing requires a good basic understanding of steel to steel connections as they depend upon several factors. Primary questions to consider would include:

- What is the position or role of connection? – beam to column, beam to girder, within a truss, etc.
- Structural requirements of the connection? – is it to transfer tension, compression, shear or moment?
- What types of structural steel members are being used? Shapes, tubes, plates, rods?

- Is the connection to be exposed (i.e. AESS), or concealed? As this will determine the budget or care that will be ultimately devoted to detailing this or any connection.
- Does either the structural requirement for the connection, or its tectonic role in the structure give preference to bolted or welded connections? Does anything else limit the connection method?

Teaching Aids:

Different methods of addressing the base teaching of connections can serve to both compliment each other as well as give students a better grasp of the subject. Engagement should not only include standard texts and illustrations, but in order to be effective, should also include "real" or "tactile" examples. Compare the two examples below. On the left is a detail from a textbook, showing a steel-to-steel connection. On the right is a full-scale installation that includes a wide variety of real connections using actual steel members and connections. Both teaching aids provide insight and instruction. The full-scale mock-up adds particular value in assisting students in understanding the actual size and texture of the finished product. Neither speaks to the important area of process or constructability.

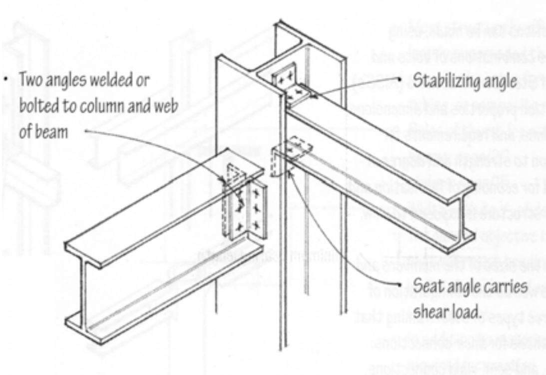


Figure 5 (left): Excerpt from Francis Ching's "Building Construction Illustrated".[3]
Figure 6 (right): CISC Member donated Teaching Aid installation at the University of Alberta.

As part of an initiative to both educate and engage students in the rudiments of steel detailing, the members of the Canadian Institute of Steel Construction have donated full sized teaching aids to most of the schools of engineering across Canada. These have proved helpful as the nature of steel construction would preclude most hands-on learning experience.

Once basic connection knowledge is learned, students can progress to the examination of more complex details. Dissection of such details to understand their structural and connective functions as well as the modifications that have been made to realize more artistic conclusions, can assist students in the development of an expanded vocabulary of connections. If one compares the textbook illustration to the in-situ arrangement, it is not difficult to expect students to make such jumps of their own accord in design projects.

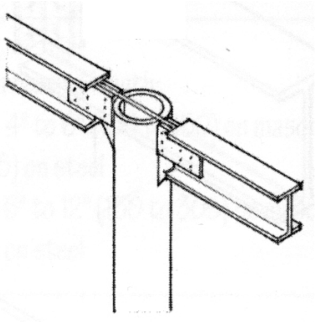
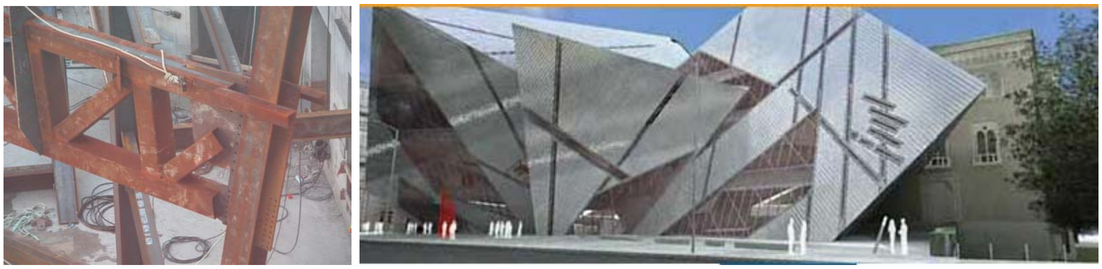


Figure 7 (left): Detail from Ching of a type of tube to WF connection
Figure 8 (middle): Detail of tube to tube connection with plate on the Leslie Dan School of Pharmacy
Figure 9 (right): crane lifting pod segment for placement

The examination of a number of case studies can begin to realize, for example, the useful role of the plate as intersector between round tube connections and as a means of resolving more complex geometries than are easily solved with complex tube to tube connections as illustrated in Figure (above). If the construction erection sequence is also known, it will become apparent that the hierarchy of connections also responds to the need to break the structure into discrete units that can be easily bolted together on site. Transportation images will reveal limitations that are placed on assemblies due to shipping concerns. Bolting of important intersections may be seen as preferable to welding operations that are normally relegated to the fabrication shop when at all possible to provide for better ultimate quality control. Included is the need to illustrate images showing temporary seats or shoring that permit iron workers to complete on site bolted connections, prior to achieving stability in the structure.

IDEAS BEHIND AESS – LIBERATING OR LIMITING?

Leaving the steel exposed in the final building makes it much simpler to find good examples with which to teach. However, the view of incorporating AESS into a design can be vary from liberating to highly restrictive. If steel is not intended to be exposed, compositional considerations of the structure can be seen to matter little to the designer. Much of the recent work by Architects Frank Gehry and Daniel Libeskind, uses intense quantities of structural steel in frenetic designs – but in an ultimately concealed fashion. There is little artistry in the actual design of the connections, whose main function is to provide enough material to accommodate adequate numbers of bolts or welds. Although something may be lost in the educational potential of this type of construction, there remains some prospect for case study learning and inspiration through the examination of the design and construction process. These projects tend to engage students in ways that traditional construction does not. Engagement needs to take place in order to propel learning.



Figures 10 and 11: ROM steel under construction and the rendering of the completed building.[4] The steel will be, for the most part, concealed beneath gypsum board.

A study of the actual erection sequence on such projects is capable of providing a greater insight into the issues associated with transportation, staging, erection and accuracy of fit, than would be the case for more standard construction that would have less demanding geometrical complications. Such was the case for the installation of a large truss at the Leslie Dan School of Pharmacy in Toronto. A 50 tonne full storey truss was erected at the fifth floor level of the building, atop a leggy concrete atrium. The truss will ultimately be used to suspend a "pod – classroom" within the atrium space below. The truss required precision alignment in a vertical slip joint at one end, a beam connection at one-third down the length, and alignment atop a column at the end point. Complex structures require great precision in fabrication, erection and alignment, as well as skilled ironworkers working at some risk to install large steel pieces. The study of such processes can highlight to the students the need for accuracy and constructability of details and connections. Students often have the mistaken impression that connections have a good deal of "play" in their fit – when the opposite is actually the case. Lack of precision can compound dimensional discrepancies that can ultimately mean unnecessary refitting of elements on site. Or in the worst instance, complete replacement parts that require special re-fabrication that cause construction delays.

Figures 12 and 13: Leslie Dan School of Pharmacy, University of Toronto, Norman Foster – erection of a 50 tonne steel truss at the fifth floor level.

Construction sequencing for architecturally exposed steel members places further limitations on detailing and increases the challenge of erection. The 90 foot long steel columns pictured below were pre-painted at the fabrication shop with a fire resistant intumescent coating. Not only was the street access extremely restrictive, but care had to be taken to preserve the integrity of the intumescent coating during handling and erection. A custom set of supports (blue) was constructed to hold the members in place until such time as proper lateral bracing could be provided.

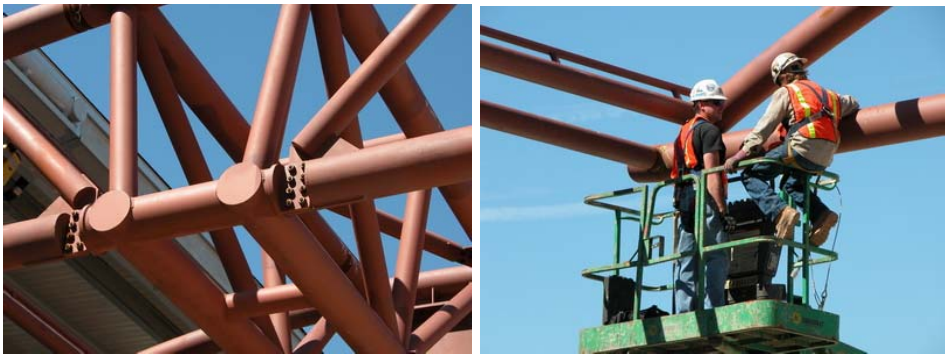
Figures 14, 15 and 16: Erection sequence for HSS legs on OCAD project. Photos: PCL Construction.

Architecturally exposed structural steel specifications place a higher level of requirements on ironwork, that lie above and beyond the regular structural and safety aspects of steel construction, in their additional address of aesthetic and design considerations. These requirements are outlined in the Master Specification section: SECTION 05125 – Architecturally Exposed Structural Steel. Not only must more care be taken during the shop and field fabrication of AESS product, but other operations, beyond those of normal fabrication, are necessary to raise the aesthetic and tectonic level of the steel for purely visual and tactile goals. The steel must be seen to be smooth and defect free. It may also be required to be touched and felt to be smooth and defect free if situated at the public level. If bolted connections are used, this may not be a difficult requirement as the tectonic characteristics of bolted connections are perceived to be somewhat "busier", and the structural steel or tube itself is unlikely to require more than proper paint finishing. However, when welded connections are specified, extra expense is usually incurred by the addition of grinding operations. This has much to do with the perception of welded connections as being smooth and physically seamless. Welds, particularly if done by an unskilled worker, can be seen to mar the fluid appearance of the final product. Specialty elements that require steel to be cast into unusual shapes, or bent into complex curves, also places additional requirements on the fabrication and installation that will increase the cost of the steel well beyond the norm.

Such information needs to be conveyed to architects (and architectural students) so that they understand the impact of "line items" in specifications. Grinding and filing operations are time consuming, hence costly, and can be quite unnecessary if the steel in question is not in a position for close scrutiny, via sight or touch.

Figures 17, 18 and 19: An AESS Sample Board, Fillet Weld Sample, Groove Weld Sample[5]

In order to prevent legal issues resulting from misunderstandings regarding the quality of the finished product, AISC recommends the creation of a sample board for each project to illustrate the final expected result. Such a board should be accompanied by a cost break out to assist in differentiating the project costs related to high finish requirements in the exposed steel. Designers are then in a better position to both understand the product as well as the associated costs.



Figures 20 and 21: AESS installation at the expansion of Baltimore-Washington International Airport. Workers are busy grinding all of the welds smooth to achieve specified finish standards. If welds are properly completed in the first instance, it is highly unlikely that passengers waiting for taxis under this canopy will ever appreciate the extra time and cost to grind each connection.

USING CASE STUDIES TO EXPAND VOCABULARY:

Although I have been using Edward Allen's "Fundamentals of Building Construction" as my course text since I saw it introduced at the very first ACSA Technology Conference in the early 1980s, it is necessary to take students beyond the basics of connections, as addressed in this and numerous other building construction source texts, and expose them to the potential "play" that lies in detailing. If you comprehend the basics, *the fun lies in really detailing the structure*. Case studies are an excellent way to tie basic construction teaching to an elevated presentation of architectural design. Real buildings can show students how to take the principle ideas of connections and begin to create expression in their structures and buildings.

Creating Case Studies:

Thorough case studies are not easily found. The majority of glossy publications normally include only images of the recently finished building, and rarely any construction images or connection details. If in the final instance, the steel has been left exposed, such finished images can be useful when discussing the building. In the case of concealed steelwork, finished images give no useful information with which to address construction and detail related concerns. It may not even be apparent that the building is constructed using steel!

Creating good case studies "from scratch" that can address the wide range of issues related to the teaching of structural design from an architectural viewpoint, requires not only dedication, but also "being in the right place at the right time". Access to construction sites is not always available, nor necessarily, is the time to make repeated visits to obtain sequence shots. Student field trips are difficult to arrange (although excellent opportunities for learning), and rely on a certain degree of serendipity – hence giving students in subsequent years an uneven chance of touring through a "good" building. Although constructors are required to document the construction process, these images are in many cases taken for legal protection, and most constructors are not willing to share or publicly distribute their images for the same reasons. Fabricators can also be guarded due to production "secrets" (particularly in the case of challenging and highly competitive AESS work) – or simply don't take an interest in documenting the process.

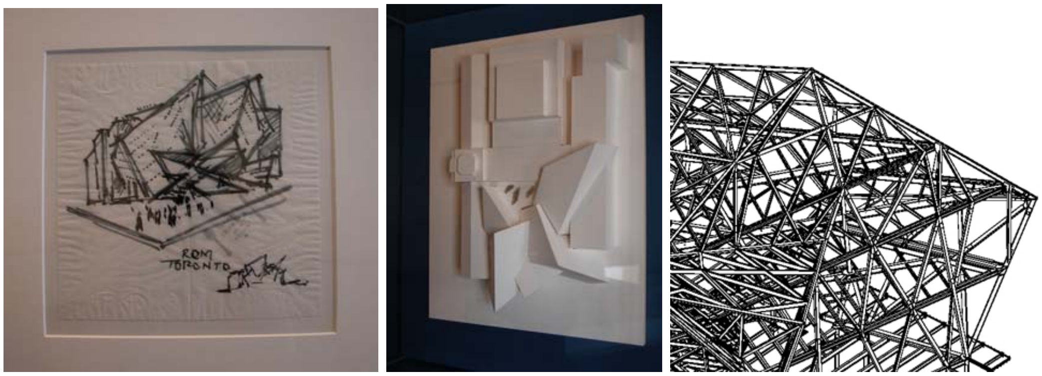
For a case study to be truly useful, it must address the entire design and construction process. In this way, as an educational tool, it can be used to bridge the gaps that currently exist between teaching areas in most schools of architecture. A *thorough* case study requires:

- knowledge of the design intentions of the architect
- access to design sketches, models, computer renderings
- detail drawings that show the relationship between the structure and the skin
- connection development from an engineer's or fabricator's viewpoint
- fabrication images
- transportation images
- erection sequence images
- video footage, if possible, that can explain the actual erection process
- completed images

The final case study must be presented or available in a form that can be easily adapted to the specific course with respect to style of teaching/learning, amount of time available to address issues and the experience level of the students. Usefulness also unfortunately is dependent upon the technologies available at varying schools: from slide projectors, to DVD, to Powerpoint^{TM} or video. Based upon conversations with professors of architecture, the *least* easily used format seems to be video, particularly if the run time exceeds the amount of time available. The most useful formats would be sets of digital images or slides, if accompanied by a "script or narrative" that explains the project, and CD-ROM or DVD format presentations that allow the instructor to select portions of a case study for use if time or subject area does not permit the inclusion of the full case study. Image based data that can be accessed via the internet for either download or direct use is helpful as it increases the ease and immediacy of access.

The Beginnings of a Case Study:

These early images represent the *seeds* of a case study. The project is the Addition to the Royal Ontario Museum in Toronto, Ontario by Studio Daniel Libeskind. The project is of enough interest to the Museum itself to have become an interactive exhibit of sorts. The museum exhibit includes the classic "napkin sketch", preliminary massing models, developed architectural models, detail drawings and renderings of the proposed gallery spaces. Numerous window openings in the museum have been created to allow an overview of the site and construction progress. The technology that has allowed online construction viewing via webcam is of benefit to educators who may wish to track and document construction changes.[6] This is also provided for this project.



Figures 22, 23 and 24: ROM Addition, Daniel Libeskind: napkin sketch, massing model, isometric of steel for one crystal

Figures 25, 26 and 27: ROM Addition, Daniel Libeskind: X-Steel joint detail, shop fabrication at Walters Inc., Hamilton, Ontario, erection (project under construction as of September 2004)[7]

The most unfortunate aspect of the ROM addition, and many similar projects, is that this complex steel structure will be completely obscured from view in the final form of the building. Hence, once complete, the building fails to serve well as a "live" example of structural steel design and construction. This was also the case with the recent addition to the Ontario College of Art and Design in Toronto, by British Architect Will Alsop.[8]

Figures 28 and 29: OCAD Addition, Toronto. During and after construction.

Due to fire regulations, 90% of the structural steel of the "table top" was concealed behind gypsum wallboard finishes at the fifth and sixth floor levels of the building. Had this educational facility NOT been propped atop 93 foot long HSS tube legs, i.e. if placed at ground level, the steel could have been left exposed!

Existing Case Study Databases:

The Steel Structures Education Foundation (SSEF) under the umbrella of the Canadian Institute of Steel Construction (CISC), is currently producing a series of CD-ROMs that address the development of steel case studies that utilize both regular structural as well as architecturally exposed structural steel, for use by educators. These have been distributed free of charge to architectural students across Canada. The first CD-ROM covered the construction of BCE Place in Toronto, by Santiago Calatrava, as well as the design and construction of the Vancouver International Airport by Architectura. The Calatrava building uses specialty AESS shapes to create an exposed steel galleria that provides a covered urban walkway in the downtown core of Toronto. The Vancouver International Airport studies the use of AESS in an exposed moment-frame construction that also includes a significant suspended walkway through the building. Of additional interest is the seismic design that has been incorporated into this building. The disk uses a format that allows navigation through the material so that discrete parts may be used, as well as containing a folder of jpeg format images as well as mpeg video that the instructor may incorporate into their own Powerpoint^{TM} presentations.

Figures 30, 31 and 32: BCE Place, construction and finished images. Excerpted from SSEF Case Studies CD-ROM Volume 1.

The second CD-ROM, due to be released in the Winter of 2005, looks at the design, fabrication and construction of the 11 new Skytrain Stations that comprise the extension to the Vancouver Millennium (above grade) Transit extension. These stations make predominant use of AESS steel, either exclusively or in combination with large wood/glulam construction that is characteristic of British Columbia architecture. Documentation focuses on the construction of the stations as well as the finished project.

The third in the series, due for release in 2006, will include three high profile buildings, presently either complete or in the early stages of construction: the OCAD Addition by Will Alsop, the ROM Addition by Studio Daniel Libeskind and the Leslie Dan School of Pharmacy at the University of Toronto, with Sir Norman Foster as Design Architect. When ready, copies will be available from CISC for a nominal shipping charge.

In addition to the series of educational CD-ROMs, CISC also maintains a constantly expanding online gallery, in html format, of significant steel construction, for use as a reference base by the profession at large.[9] AISC also provides case study information online, in pdf format. Online case studies are most useful if the images are easily downloaded as jpeg files. The pdf is more difficult to manipulate as the image quality is often compromised to decrease file sizes.

The Steel Tube Institute of North America is in the process of revamping its current set of online case studies, as well as expanding its effort to create more detailed case study material for use by architectural educators. It is anticipated that part of this package will be available by the time of the ACSA Annual Meeting in 2005, with the balance ready for distribution in 2006.[10] It is the goal of the Institutes to provide high quality teaching materials as a means to further stimulate the education of students in the area of steel design, to promote good and innovative steel design, and to foster a healthy relationship between the industry and the profession.

STUDENT DESIGN COMPETITIONS – TAKING DESIGN TO THE DETAIL:

It is often the nature of the architectural studio design process to realize student projects that lack the level of completion that is ultimately required of real world projects.

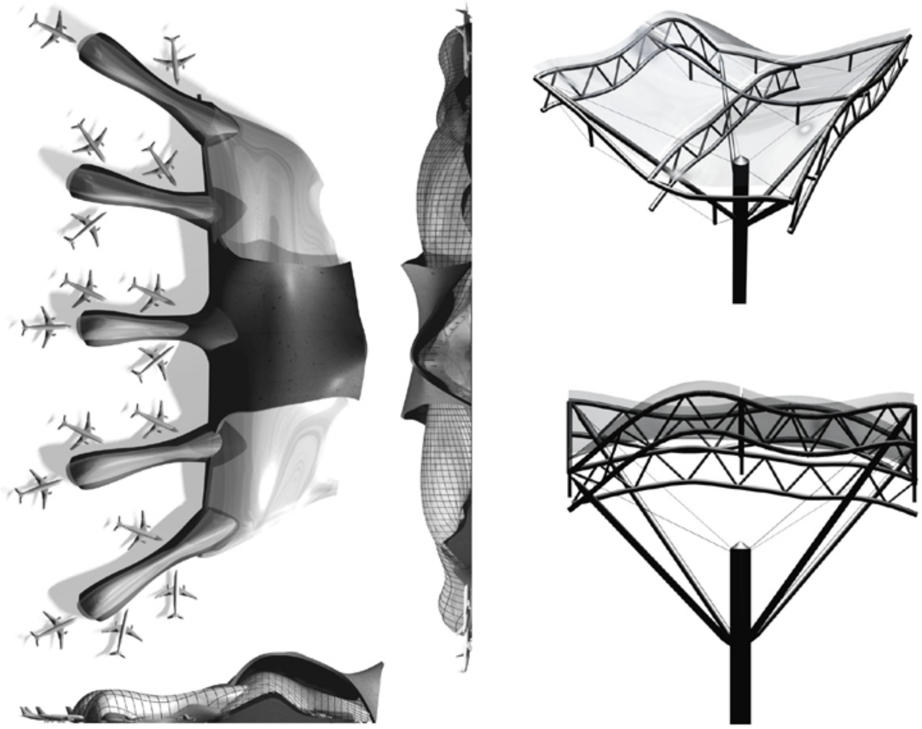
Lack of such detailed resolution removes much of the potential learning that can take place through the maturity of detail that can occur in the later stages of design development. Many schools lack the crossover between construction, structures and studio courses that would allow either the time *or the incentive* to develop a project to an extremely high level of detail – the type that is central to an architecturally exposed structural steel design. Without adequate development, student projects will see no more meticulous connection development than can be seen in the wood models of the steel construction proposed for the Addition to the Art Gallery of Ontario by Frank Gehry, pictured below. In the case of these models, it is not as much an issue of lack of thought, as the limitations of the scale and medium of the model. Detailed connection development can only be illustrated at a very large scale.

Figures 33 and 34: Design models of the proposed addition to the Art Gallery of Ontario by Frank Gehry (AGO Website[11])

Learning must be followed by "doing", if the lessons are to properly become part of the competent architectural vocabulary of any designer. Competition work gives students both the incentive as well as the opportunity to develop buildings, in particular steel buildings, to a level of completion that is higher than is normal in a design studio. As with any material sponsored competition, it is known to be in the best interest of the competition to make maximum use of the subject material, and in the case of steel, it is recognized that development must include proficient as well as expressive detailing.

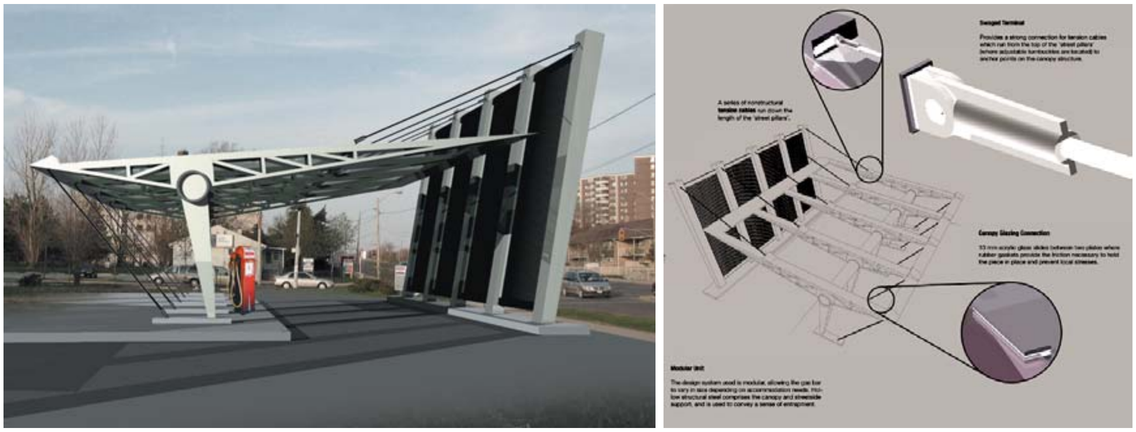
The scale of the problem is paramount in setting the competition program. If the competition is "program-dominated", the student may not have the opportunity to develop the steel to an adequate level of detail due to time constraints that result from programming and layout of spaces. Exhaustive programs for very large buildings also place many competitions beyond the reach of the junior students, who might be very interested in skill development, but who are put off by the complexity or scale of the problem. If the area of material tectonics is to be successfully developed in architectural education, junior students are the best place to start.

The competition entry below was completed by an intermediate level student, but never submitted, to the ACSA/STI Airport Competition in 2002. Feedback from the student indicated that the programmatic requirements of the project took such a degree of time that he was unable to complete the project in a timely fashion, having not foreseen to allow sufficient time (as this was done "extra" to the studio program). Although as previously stated, airports have culturally become key centers for the expression of steel in architectural design, the programmatic requirements of the typology clearly took precedence over advanced detailing of the structural system in this particular situation.



Figures 35 and 36: Details of a competition submission by Eric Bury for the 2002 ACSA/STI Airport Competition[12]

Compare the illustrations above with excerpts of details from student entries for the CISC Steel Structures Education Foundation 2003 Competition for a “Gas Bar”. The SSEF Competition was designed to appeal to entries by all levels of students. The competition has often awarded first and second place prizes to students who are just completing their first year of an undergraduate degree in architecture. The size of the competition program type is small enough to allow the students to focus on a single structural question (such as long span or cantilever), and to push the design into the large-scale development of key building details. The projects are also adequately limited in scope as to allow students to develop the projects as an “extra” to their normal course load.



Figures 37 and 38: SSEF A Gas Bar Competition 2003. Second Place. James Andrachuk and Uros Novakovic, First Year Architecture[13]

With a large-scale program, unless a design studio adopts the competition as their central focus for the term or the year (which does not often happen), students normally find themselves without sufficient time to adequately develop the project to the high level of design and presentation required of a competition entry. Hence the discrepancy between the numbers of students who register an intention to submit for a competition, and the numbers that actual send entries. In the case of the SSEF Competition, at least one Canadian School of Architecture has made the project mandatory in its Building Construction class. The focus of the final term project on the competition (although actual entry was not required), elevated the project to produce effort and results well beyond those considered "normal" for the terminal project in a building construction support course. The scale and scope of the competition was able to begin to bridge the gap between technology and design, within a technology support course.

The current SSEF competition for 2004, called "Tripping the Void"[14], calls for the design of a long span pedestrian bridge. The pedestrian scale of the structural and tectonic requirements for the bridge should allow students some freedom in their design expression – freedom that is necessary to evoke creative juices, rather than trepidation over impending structural collapse.

CONCLUSION:

As illustrated, it takes a great deal of innovative teaching and "tools", as well as effort, to bring architectural students to a level of expression in steel design that is reflective of a good knowledge base in the requirements of the material, as well as inspired thinking when it comes to the actual detailing of the material, its construction and connections. Basic construction teaching must be followed by exposure to high quality case studies that address the full range of design and construction concerns, as well as laterally develop the concepts to include a wider range of material shapes and connection details. Exploration into the requirements of Architecturally Exposed Structural Steel systems also helps to focus learning on issues of heightened requirements for quality and workmanship in connection detailing. Such learning is best developed if followed through via a highly exploratory and well-detailed design project that can come in the form of a suitably scaled competition.

If they "get there", students will discover that detailing a steel building can be a lot of fun…

BIBLIOGRAPHY:

American Institute of Steel Construction Website:
http://www.aisc.org

Architecturally Exposed Structural Steel. Modern Steel Construction. May 2003.
http://www.aisc.org/Template.cfm?Section=Technical_Answers&template=/ContentManagement/ContentDisplay.cfm&ContentID=25153

Art Gallery of Ontario Website: http://www.ago.net

Canadian Institute of Steel Construction Website:
http://www.cisc.ca

Ching, Francis D. K. Building Construction Illustrated. Third Edition. New York: John Wiley and Sons, Inc., 2001.

Master Specification: SECTION 05125 - Architecurally Exposed Structural Steel

Royal Ontario Museum Website: http://www.rom.on.ca

Steel Tube Institute of North America Website:
http://www.steeltubeinstitute.org/

IMAGES:

All images by author unless otherwise noted.

ENDNOTES:

---

[1] http://www.aisc.org/Template.cfm?Section=Technical_Answers&template=/ContentManagement/ContentDisplay.cfm&ContentID=25153

[2] For more information on the United Airlines Terminal at Chicago O'Hare, please refer to: http://www.cisc-icca.ca/ohare.html

[3] Ching. p. 4.18

[4] Image of completed building taken from ROM Website: http://www.rom.on.ca

[5] Architecturally Exposed Structural Steel. Modern Steel Construction. May 2003. http://www.aisc.org/Template.cfm?Section=Technical_Answers&template=/ContentManagement/ContentDisplay.cfm&ContentID=25153

[6] ROM Webcam: http://www.rom.on.ca/webcam.php

[7] For additional information on the ROM Addition, Toronto, Studio Daniel Libeskind, please visit: http://www.cisc-icca.ca/rom.html

[8] For additional information on the OCAD Addition, Toronto, Will Alsop Architect, please visit: http://www.cisc-icca.ca/ocad.html

[9] CISC Website: http://www.cisc-icca.ca

[10] For additional information on Steel Tube case studies, please visit: http://www.steeltubeinstitute.org/hss.htm and click on "Obtaining Literature".

[11] Website for the Art Gallery of Ontario: http://www.ago.net

[12] http://www.fes.uwaterloo.ca/architecture/faculty_projects/terri/bury2.html

[13] SSEF Competition website: http://www.cisc-icca.ca/and_nov.html

[14] SSEF Competition program 2005 "Tripping the Void": http://www.cisc-icca.ca/ssef.html#void