The Dynamic Phraseology of Structures: Enabling the Design of Complex Systems

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ABSTRACT: The discipline of structures can be compared to that of language. The scholarly approach to the thorough learning of a language can be likened to the complete study of structural design and analysis as taught in engineering and achieved through years of practise. Architects may benefit from learning the rudiments, but without expansion, such learning fails to enable an approach to complex designs. The study of "architectural structures" could benefit by being taught as a conversational language. This presentation puts forward an alternate approach to teaching steel in particular, that builds upon traditional numeric and materials type instruction. *It proposes a method of teaching that looks at structures in a three dimensional non-numeric way in order to better influence the students' ability to incorporate structural phraseology into their design projects.* The paper proposes a *forensic* approach to the investigation of exemplary structures to better understand the collaborative nature of structural steel design, requiring a high level of communication between the architect, engineer, and the steel fabricator, and building upon the plain language of simpler, rectilinear systems.

1 INTRODUCTION

Architecture and engineering succeeded in dividing themselves into distinct professions towards the early part of the 19th century. In the time between the Renaissance, where humanism placed the architect at the center of the design project, and the 19th century, many material and physics related discoveries took place. The "mathematical" aspects of design expanded to the point where specialization seemed necessary. The discipline of civil engineering emerged. Over the last 200 years it has become standard practice to assign the detailed design of the structure of the building to the consulting engineer. This is due in part to the inability of the architect to do this work, complemented by the need to assign the legal liability for this work to the engineer, who has the appropriate education and expertise.

Prior to the invention of the personal computer, and recent innovations in 3-dimensional design and detailing software, structural systems were relatively simple to solve as they were predominantly rectilinear and able to be resolved into simple 2-D determinate structures. This was certainly the case for steel buildings due to their straightforward framed construction, if less the case for concrete structures which tend towards indeterminacy. Sliderule-based limitations in the ability to calculate structures had a direct bearing on what was designed and constructed which aligned well with Modernist and International Style tendencies of the 20th century. This might be seen as a "chicken-and-egg" observation. It may not be determined which came first, but the general outcome, regular orthographic systems, is the result.

Formalized, professionally directed architectural education that developed during the 20th century has typically included a simplified engineering approach to teaching structures to architects. Even before architectural certification boards and professional accreditation of architectural programs began to regulate curriculum, most schools included some form of structures teaching in their coursework. The expanded regulatory oversight of the boards during the last 20 years, and the nature of the registration exams that must be written in order to enter the profession, has seen an even more widespread adoption of numerically based structures courses into the architectural curriculum. This has been done to address professional competency and increasing liability issues. However as the requirement is written in the 2009 NAAB Criteria, the specific teaching method has not been prescribed.

> "B. 9. Structural Systems: *Understanding* of the basic principles of structural behavior in withstanding gravity and lateral forces and the evolution, range, and appropriate application of contemporary structural systems."

Therefore the persistence of teaching radically abbreviated engineering methods to architects is not actually required in terms of this outcomes based type of assessment. If you replace the word "understanding" with "ability", then you could have a different situation, but not necessarily so.

> "The criteria encompass two levels of accomplishment:
> ***Understanding***—The capacity to classify, compare, summarize, explain and/or interpret information.
> ***Ability*—**Proficiency in using specific information to accomplish a task, correctly selecting the appropriate information, and accurately applying it to the solution of a specific problem, while also distinguishing the effects of its implementation."

Although these criteria may vary globally, this is given as evidence that it is possible to question the status quo and look for a more effective way to enable architects to design complex structural systems.

2 FROM PLANAR TO COMPLEX PROBLEMS

The numeric, orthogonally based, engineering approach to structural design teaching has not changed appreciably in 200 years. Where this 2-D computational method may once have been relevant in preparing architects to discourse with engineers, it does little to facilitate understanding or ability when designing complex, non-rectilinear structures. One has only to recall the difference between solving a 2-D and 3-D node in a truss to imagine the challenge of designing something larger and with irregular geometry.

"Rules of thumb" were designed to link standard structural teaching with built examples. Over time and with experience we come to be able to simply look at a simple structure and sense whether or not it is sound. With rectilinear structures the overarching sense of structural order allows this to happen. From the perspective of the experienced architect, and in terms of the impact that such decisions ultimately have on the design of the building, if beam and column sizing are with certain tolerances, the precision of sizing determined by the engineer is not very likely to cause a problem. This is not the case with complex buildings. The proliferation of odd geometries and eccentric loading will challenge even the most experienced of engineers. Member sizing and connection design is no easy task and it is difficult to create a comfort level where there is inconsistency in examples and no "rules of thumb".

The complexity of built architecture has changed radically over the last 30 years – lagging slightly behind inventions in computing hardware and software. Frank Gehry was one of the first firms to embrace the potential of 3-D modeling software as a means to facilitate complexity in design. Gehry Technology was charged in 2003 with making a version of CATIA software easier to use for the AES market. Over the last 10 years programs like 3D Studio Max, Form-Z, SketchUp and Rhinoceros have become common place architecture schools and offices. It is not difficult to think back to a recent time when such programs were looked at with suspicion and fear of the loss of hand drafting skills.

These 3-D modeling programs have propelled architecture in a direction that is beyond simple methods of analysis. Where such programs can truly liberate design thinking, 3-D modeling can also provide a false sense of believing that structures are sound, simply because they can be modeled. The understanding of complex structures must change to reflect complex structural design and detailing requirements.

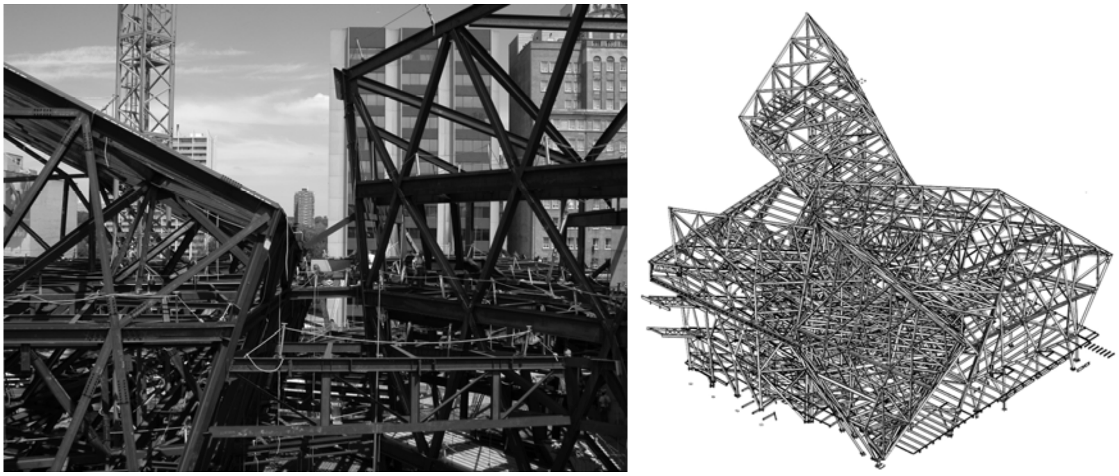

Figure 1. (Left) The structural steel in progress for the addition to the Royal Ontario Museum in Toronto, Canada, designed by Studio Libeskind. (Right) The 3-D isometric that was generated by the fabricator’s design and detailing software. A project this complicated would not have been possible without the use of sophisticated software. There are no vertical columns. Nothing is even remotely able to be solved using simple statics.

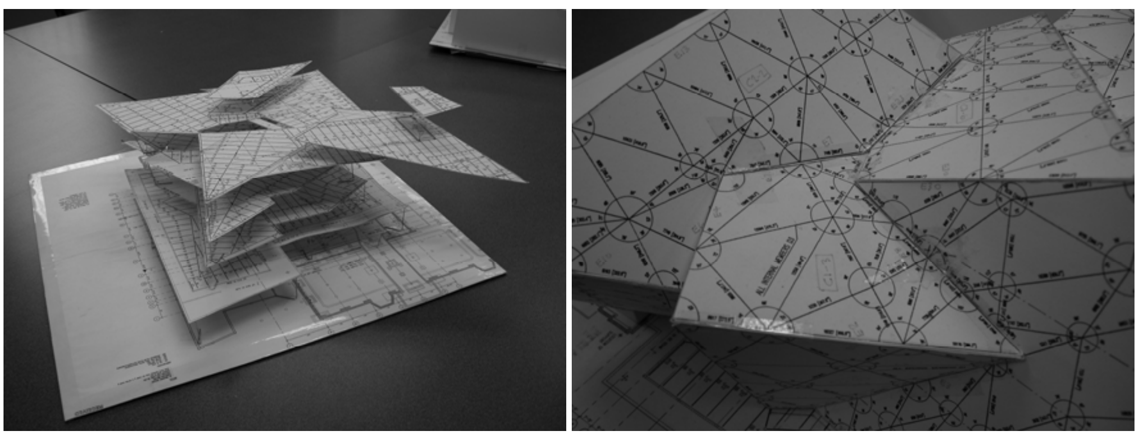

Figure 2. Even the steel fabricators must resort to clarifying measures when working through an understanding of complex structures. (Left) A paper model of the floor plates of the ROM. (Right) a paper model of the diagrid faces to show the framing pattern. The architect, engineer and fabricator found 2-D traditional forms of drawing completely useless on this project. For the most part they were only produced for the building permit submission.

3 THE MATHEMATICAL BRAIN

All of this is *not* to say that mathematics and the learning of simple structural calculations in statics, strength of materials and analysis is unimportant for architects. There is an important balance to be achieved between “the artistic brain” and the “logical brain” (also known as right brain and left brain). The logical brain is responsible for language and mathematics. Hence the learning of structures as *phraseology* will necessitate some activity from both sides of the brain. There is also significant belief that mathematics is beneficial exercise for the brain.

The question becomes “What is the *optimal amount* of numerical structures for architects?” There has to be enough to be meaningful and provide a solid grounding in the understanding of balance, stability, loading characteristics and material strengths. Architects need to appreciate the impact of loading on beams, columns and planar trusses. They should understand the differences between compression and tension members so that they can use this information to allow size/material differentiated member choices. They need to understand shear, moment and deflection diagrams in order to appreciate the way that loading works as well as the impact of span length, cantilever and load transfer. Should architects know how to size the rebar in a reinforced concrete structure or the bolts in a steel framed connection? Likely not. These sorts of exercises focus in too closely to a part of the overall problem of structural design that by itself is quite abstract and fairly useless. Architects typically do not design or calculate the structures for other than smaller residential buildings. And for these there are often simple span tables to assist with member selection.

If it can be said that architects are ill prepared to design (complex) structures as a result of being educated with antiquated methods that were best suited to simple structures, then the same can likely be said of engineers who have typically had even less architectural content in their education. This may beg the question, "Why do architects need to learn structures?" The simple answer might be to be able to have an intelligent conversation with their consulting engineer. In reverse it is also likely that engineers need to better understand the interdependency between the structures that they design and their impact on architecture.

If looking at customizing the teaching of structures for architects versus engineers, assuming that architects have a more dominant "artistic brain" and engineers have a more dominant "logical brain", then the characterization of the type of structural material must start by arousing the side of the brain that is most comfortable with the material and then venture into the less active territory (although this might not work for all learners).

Ultimately, the simple rectilinear projects of the last century are becoming less pervasive in contemporary architectural design due to a level of geometrical liberation provided by 3-D modeling software, and going forward both the architect and engineer must be able to address more complex structures. This cannot be effectively solved by traditional methods of teaching and learning.

4 STRUCTURES AS A LANGUAGE

The discipline of structures can be compared to that of language. The scholarly approach to the thorough learning of a language can be likened to the complete study of structural design and analysis as taught in engineering. Architects may benefit from learning the rudiments, but without expansion, such learning fails to enable an approach to complex designs. The study of "architectural structures" could benefit by being taught as a conversational language. A concise grounding in the ability to understand and solve planar forces and material limits could then be applied to the development of a highly visual vocabulary based in "structural phrases and systems" – e.g. systems, connections and details that have been extracted from innovative and compelling projects.

Part of this language based critique of the current methodology stems from the sense that the present system is not teaching *enough* to be useful in today's world of increasingly complex buildings. The comparison to language posits that engineers are taught to use most of the alphabet where architects are given a couple of vowels and consonants. Where the architects might be able to put together a few short words, they cannot create a building with these words. The engineers might have the entire alphabet, but are also not given the architectural grammar to assemble their words in compelling ways. Although we cannot teach everything in the professional degree program, we cannot leave most of the comprehensive learning to take place during internship and practice.

Borrowing from language theory we need a *frame-based terminology*, grounded in a *structural syntax* that is comprised of a *critical vocabulary*. This would exceed the standards of a "Traveler's Phrase Book", but educate with the goal of enabling a high level conversation between the architects and engineers on the team. Words (elements or connections) will be assembled into phrases (larger aggregations such as trusses, floors or frames), into sentences (larger system elements of the structure) and ultimately into paragraphs and stories (building and buildings).

Frame-based terminology maintains that trying to find a distinction between terms and words is no longer fruitful or even viable, and that the best way to study specialized knowledge units is by studying their behavior in texts. Transferred to structural teaching this would suggest that looking at a structural member or connection is most beneficial if studied in the context of the system in which it is situated.

Structural syntax refers to the study of the principles and processes by which sentences are constructed in particular languages. Again the structural elements (members and connections) need to be situated as the way that the members and connections are assembled will vary from project to project and this will impact the way that they are designed and detailed.

Critical vocabulary infers that the selected elements, phrases and terms are essential to the development of this structural language to the point that they will form the basis for criticism in the discipline. The very basic typical connections in structural applications will form a solid base from which to explore more complex phrase-based variations which themselves can be used in a reductive or analytical way to verify if the transfer of forces is correct. But to develop a vocabulary, these must be extended and developed to have agency in architectural design.

5 IS THIS NOT BUILDING CONSTRUCTION?

It might be argued that this approach is already covered in Materials and Methods courses. Although some construction-based courses do address structural issues, these are usually limited by curricular time constraints. Practically speaking, within one or at most two lecture courses in materials and methods, there are simply too many topics to cover. The outcome-based directive for these courses is very broad and used to satisfy a large number of accreditation requirements, including understanding in building envelope systems and building materials and assemblies. The impact of climate and region is layered over this, increasing the time spent on these very important areas of study and reducing the time to more fully explore structures as the assumption may be that these are being adequately addressed in Structures courses. I would argue that meaningful teaching and exploration of structural systems and detailing is falling in the gap between the calculation-based and materials-focused courses, which may also be taught by different instructors who might wrongly assume that more is being accomplished in the other class.

6 WHY STEEL?

The basic concepts of statics, strength of materials and analysis are universal and independent of material choice. This knowledge therefore fits well as a point of termination, in terms of exclusive calculation based study and departure, for more innovative and analytical approaches. Once a structural material is introduced to the problem (steel, reinforce concrete or timber) the outcomes vary significantly as a direct result of the strength limitations of the material, its physical characteristics and its preference for tensile or compressive loading. If looking for the most predictable outcome for a teaching/learning experience, steel will provide the most certainty as a result of its homogeneity and self-use for connections. Reinforced concrete design is complicated by the interdependence of the two materials and the tendency to be used in indeterminate structures. Wood varies by species and must also contend with natural defects as well the normal use of metal fasteners, thereby becoming a two material system.

Steel already has a very well established basic vocabulary in terms of standard member shapes and typical connection methods and design. This vocabulary is shared by both architectural and engineering disciplines so is a good spring point to extend into a more complex language. Connections in and of themselves make little sense without the context of the system in which they play a role, and further into the overall architectural concept for the building. Unlike reinforced concrete with reinforcing that is hidden from view, steel connections are quite visible and easy to look at in a critical way. Where plain structural steel is hidden from view as well once finishes and cladding are applied, Architecturally Exposed Structural Steel (AESS) permits study long after the construction is complete. As a point of reference for structures teaching, AESS is good as the steel must simultaneously satisfy both aesthetic and load path considerations, and so effectively must synthesize architecture and engineering concerns.

6.1 *The Importance of Developed, Compelling Case Studies*

Detailed case studies are extremely useful in garnering student interest in structures. These must be of very high quality buildings and present a range of approaches to the creation of structural systems that are easily dissected to gain an understanding of their load paths and associated connection details and member choices.

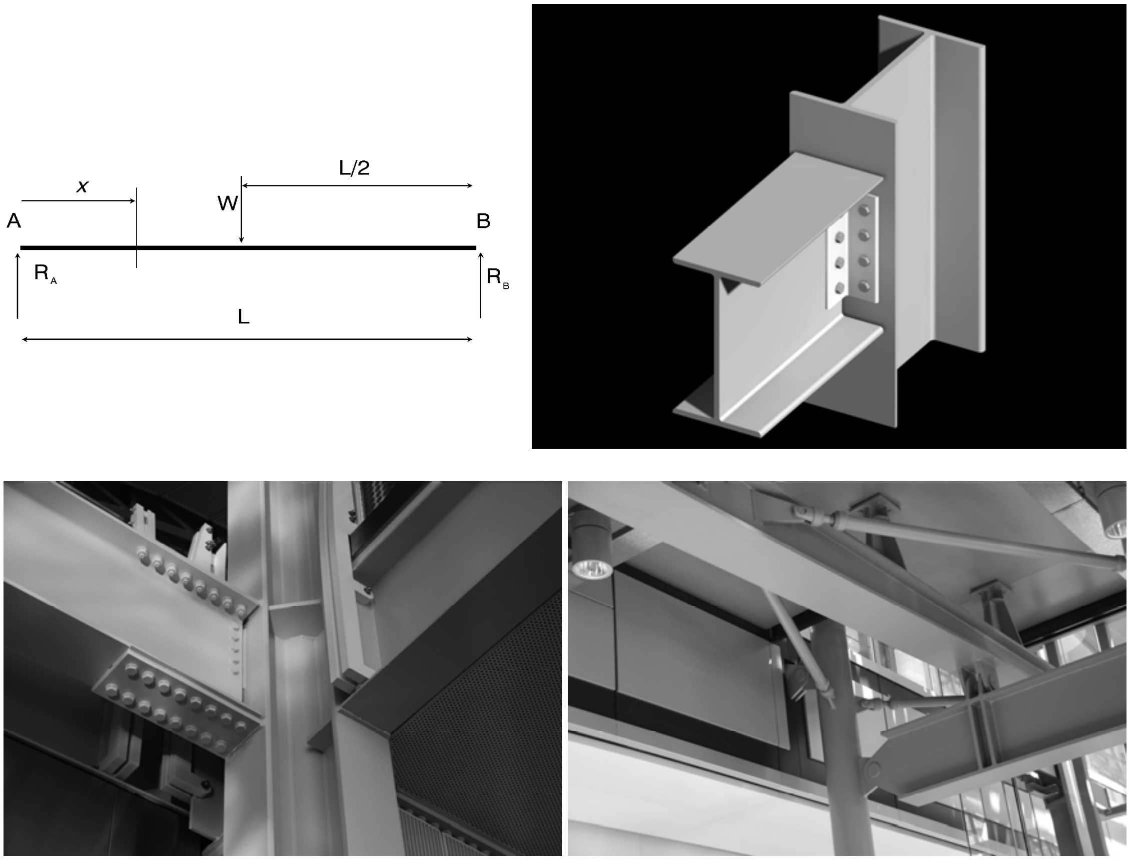

Figure 3. The diagram at the top left typifies a basic calculation for a simply supported beam with a point load. At the top right we have an example of a basic shear connection that might be used to connect the beam to the column that might be referred to by the diagram. At the bottom left (Reagan International by César Pelli) we have a more innovative extrapolation of the same detail – one that has associated issues of tolerance and design. At the bottom right (Heathrow T5 by Richard Rogers) we see another example that takes the idea of shear transfer and connection type further. Diagonal braces ask additional questions about stability issues.

The set of images in Figure 3 characterizes a simple example of the developed relationship between structural words, phrases and paragraphs. Typical structures courses will seldom get into a discussion of the most complex phrase and how it is ultimately part of the larger language of the building. The more complex the project the less likely it will be for students to calculate the forces in the members and determine the proper member size. However, it is very possible to analyze a detail and larger complex system and trace the path of the gravity loads through the members and their connections. A well designed building that uses differentiated member sizes to reflect the tension or compression role of the members can make a positive additional contribution to the learning exercise. It is important to first validate the inclusion of the example and not all structures necessarily accurately reflect the magnitude of the force being transferred through the member by virtue of its size.

If you were to use the Heathrow detail from Figure 3 (bottom right), it would be fairly easy, by seeing the larger context of the detail, to begin to determine the requirements of the connections as well as of the members – at least to the point of noting shear forces and relative conditions of tension and compression. Again, as part of a more complete language the smaller aspects of the function of the joints must extend into a larger understanding of the role in the greater structural system. Beyond this, examination of the way that the connections have been done (bolting, welding, pins) can lead to “educated speculation” of the erection process and possible issues with constructability. This I refer to as a forensic type study.

6.2 *The SSEF Curriculum Materials Project*

A web site has been produced by myself and Vincent Hui of Ryerson University, with funding from the Steel Structures Education Foundation of Canada that begins to apply the language analogy to a structural steel education resource. “Fun is in the Details: Innovations in Steel Connections” focuses on defining a frame-based set of terms for steel construction by looking at the relationship between standard methods of connecting steel, through to the design of standard connections and into a wide array of examples of various innovative connection types. The project is a “no numbers” exploration of the language of steel structures.

One of the interactive features of the site is the use of 3-D PDF drawings of the larger case study buildings. The 3-D PDF is a new file format created by Adobe that with a mouse click, loads a drawing that the viewer can manipulate. It can be rotated and zoomed. Parts can be isolated for closer examination. Standard orthographic views can also be loaded as well as particular views that have been pre-determined by the file creator. The idea behind allowing the (student) user to “fondle” the details is to permit a more intimate exploration of the connections and systems than is normally available via static line drawings or even detailed photographs.

The case studies include more historic High Tech architecture, a typology that led to the development of contemporary AESS projects. High Tech created its own language of connections, quite different from the rational orthographic use of steel typical of the Modern Movement. High Tech introduced tubular material and pin connections in addition to a tendency towards differentiated material sizes able to express tensile versus compressive members. Indeed many of the more “standard” details that formed the kit of parts for these projects have been contemporized and continue in use in today’s AESS projects.

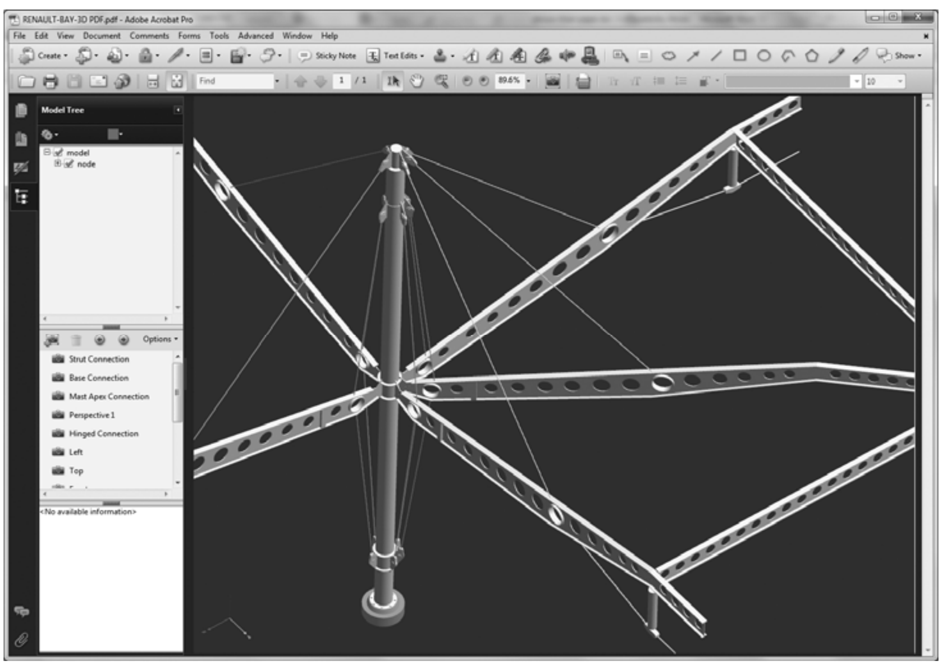

Figure 4. This 3-D PDF of Foster’s Renault Center is able to be manipulated to allow close views of the connections and details. Notes can be added to special views of the image.

The contemporary examples included in the site attempt to present a range of more innovative structural applications which demonstrate unique variations of more standard connections. Again the 3-D PDF drawings allow the user to explore the projects in greater detail. This process of investigation and use of 3-D software responds to the issues presented earlier in this paper regarding the overall change in design software. It recognizes the limitations in examining structures in two dimensions, particularly when many of them were not conceived as two dimensional simple frame structures. Complexity needs to be appreciated in 3-dimensions.

The 3-D PDFs of the case study buildings are supplemented by detailed photos of the steel connections as a means to highlight the importance of these detailed “phrases” in creating a coherent architectural language for the project. The balance of the web site forms a complete study of the development and detailing of AESS from basic concepts of connections through to the importance of finishes. All of this is paramount in educating towards excellence in the design of both simpler and complex steel structures.

7 THE FORENSIC APPROACH TO USING CASE STUDIES IN THE DEVELOPMENT OF A STRUCTURAL LANGUAGE

The language based approach to structural learning is intended to facilitate an analytical way of appreciating and mastering complex structures. It is intended to demonstrate to students how easy it is to understand the load path tracing, details and architectural design of an existing set of structures, and then ask them to do the same with other case study examples. In this way, build an even larger set of structural examples. This forensic approach can be easily applied to existing buildings with exposed (steel) structures as a way of assessing the way the structures function, but in a very critical and comparative way – one that can be readily incorporated into design projects. This method is intended to take the language of structures from the “Dick and Jane” *Primer* approach, which ends with standard systems and details, to the “Romeo and Juliet” level, deftly handling a more complex use of structural language.

This analytical approach would be of benefit for both architects and engineers as although engineers are given a significantly more complete suite of calculation-based structural design courses, these also fail to address highly complex architecturally driven structures.

8 REFERENCES

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8.1 *Images*

– Renault Center 3-D PDF by Vincent Hui
– ROM isometric diagram. Courtesy of Walters Inc.
– All other photos by author.