ABSTRACT CALCULATIONS VS CONTEXTUAL STUDY
The Need for New Approaches in the Teaching of (Complex) Structures

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ABSTRACT

If students of architecture are not taught structural design as a means to empower them to design more convincing and compelling buildings, then what is the purpose of this part of their education? This paper examines the persistence of a calculation-based teaching methodology as a barrier to creating graduates that can confidently engage their engineering colleagues towards creating high-level solutions for increasingly complex, geometry-driven architecture.

The paper looks at the potential of context-based structural learning as a departure from the use of discrete calculations as the means to more fully engage students to increase their learning. Such context-based teaching can more naturally lead to the use of case studies as a means to transfer the structural knowledge and expertise gained from simpler structures to those which are more complex.

KEYWORDS

Teaching, structural design, calculation methods, learning outcomes, complex structures

THE POSITION:

If students of architecture are not taught structural design as a means to empower them to design more convincing and compelling buildings, then what is this part of their education for? This paper examines the persistence of a calculation-based teaching methodology as a barrier to creating graduates that can confidently engage their engineering colleagues towards creating high level solutions for increasingly complex, geometry driven architecture.

Are abstract calculations still a relevant method for teaching structures to architectural students? It is the clear intention of this paper to agitate by asking a provocative question, but not to come to a succinct conclusion about the remedy to this situation. There isn't one. There may be evidence and potential, but insufficient to drive a complete change of course. Still the question needs to be addressed. Why do we generally rely on "numbers" and calculations when we teach structures to architectural students? There are many aspects of education in general that are based on blindly following protocols that have been developed over time, without actually questioning their continued validity. I firmly believe that this is one. In reality, 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. Next to nothing is actually calculated from scratch by the architect.

The current architectural trend towards the design of complex structures lies well beyond the scope of traditional calculation-based teaching methods. This would suggest the need to begin instead with a basic understanding of structural stability and materiality and a sense for detailing as students work their way into complex structures or those with challenging geometry. A more thorough understanding of complex structures can then be derived by translating and transferring the lessons learned from simpler structures.

THE ORIGINS OF THE PROBLEM:

The basis of this problem arises from the combined issues of “time constraints”, “focus” and “need”. When the professions of Architecture and Engineering drifted apart in the late 1700s and early 1800s, Architecture followed a Beaux Arts model and focused on the design of spaces, façades, program, materiality and general layout. Structural design was for the most part done by the newly formed Engineering discipline. Both the disciplines and their respective education models took separate paths. Where the mandate of engineering education maintained an increasing focus on the development and limitations of new materials, structural systems and forms, along with the integration of the new scientific discoveries in mathematics and physics, architectural education evolved in a less directed manner. This separation of emphasis continues to this day. This feeds the fourth problem and that is student expectations. Given the historical separation of the roles of Architect and Engineer, incoming students have differing thoughts about the nature of the role that “structures” (including mathematics and physics) will play in their education.

Time Constraints:
Structural Engineers devote the majority of their academic study to courses intended to allow them to design structural systems comprised predominantly of steel, concrete and sometimes timber. There is insufficient time in the architectural curriculum to replicate this full list of courses in spite of the fact that Architects are also designing buildings with steel, concrete and timber systems. The course selection has been compressed and edited to suit time constraints of the architectural curriculum, resulting in the abstraction of many of the elements. Although it varies from university to university, structures courses normally take a significant “back seat” to courses in design, which are allotted significantly more curricular time and attention.

Focus:
Engineering and architectural curricula have different areas of primary focus and with the increasing breadth and complexity of many projects the primary focus of the Architect is typically not on the detailed design of the structure (including member sizing). This also contributes to the reduction in time available to spend studying structures in great detail. The Engineer and Architect also view the structural system in different ways. Architects tend towards concepts and visual details of the structural system, particularly if it is to be left exposed and elevated as part of the architecture. The Engineer must provide adequate technical detail to support fabrication and construction. If a concealed structural system, the Architect will have little input on the structural details.

Need:
This is in part based on the area of primary focus, teamwork as well as legal responsibility. The curriculum as it has developed responds to issues of need as curricular time is allotted. Engineers need to be able to have the skills to fully design a structural system as they are legally liable for its success. Architects need to be able to converse adequately with Engineers in order to understand and get the fullest benefit from the structural design for a project. If the structural system fails, the Architect will place liability on the Engineer. Architects seldom need to size structural members and connections, and are actually cautioned to avoid this activity due to legal liability.

Student Expectations:
The differing nature of the type of student who enters Architecture versus Engineering also will come into play. Each brings a set of preconceptions about the nature of the profession and the type of work that they are being educated to undertake. Our School conducts personal interviews of the approximately 450 top candidates to fill our 75 positions in the first year of our professional undergraduate degree (average age 18 years, coming in directly from High School). In over 25 years of personal experience in this process I have not heard one student mention detailed structural design as an objective of study. Even when their natural response to the question “Why do you want to become an Architect?” is “I am good at math, physics and art (usually stated in that order), and Architecture is the one profession that combines all three”, students still proceed to follow their artistic side and allow it to dominate.

Part of this critique of the current situation, driven by time constraints, focus and need, stems from the sense that the present system is not teaching enough to be useful in today’s world of increasingly complex buildings. If we think of structures as a language you might say 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 sophisticated legally liable structural system with these words. The Engineers might have the entire alphabet, but are not normally given the architectural grammar to assemble their words in compelling and complex ways. In both instances what seems to be lacking is a sense of context for the structural system and its related detailing and materiality. If a student does not feel empowered by the knowledge that he/she is gaining, and in fairly full and confident control of the information, he/she tends not to make use of it when designing. Again this can be compared to language. We are hesitant when we travel to make use of our "high school" French or Spanish lest we embarrass ourselves in all but the most pressing circumstances. Those tell-tale grammar mistakes reveal our lack of expertise and undermine our credibility.

A BIT OF HISTORY:

I will be autobiographical, which is usually not advised in academia, in order to establish what I see as the specifics of the problem and justify my position. I studied architecture during the late 1970s and early 1980s in a school that had its birth in a Faculty of Engineering.[1] The curriculum component titled "Systems and Measures" included the following distinct (12 week, 36 hour) courses:

- Calculus
- Statistics
- Statics
- Strength of Materials
- Structural Analysis
- Indeterminate Structures
- Steel Design
- Concrete Design
- Timber Design

All courses were exam oriented and had virtually no project type components. These were taught by engineers who had no opportunity to interact with the design studio. There were no courses in Building Construction. As it was a coop education school, it was assumed that we would "pick up" this sort of technical material during our work terms and that students would somehow manage to integrate all of this into their designs. Students in our coop program students alternate between academic and mandatory work experience, netting 2 years of experience prior to graduation from the pre-professional degree. It was always assumed that technical skills relating to construction would be acquired on work terms and therefore need not be addressed through the formal curriculum. Although our students were valued more highly than other architectural schools nearby, this was largely due to the coop education work experience and not to the ability of students to integrate any aspect of detailed structural design into their design project work. Although I was an A+ structures student, I found no way to make any connection between what was taught in the structures class and my own work. Without any discussion as to how the structure could be integrated into the design and construction of the building, most of this information was quite useless. It had no real architectural context.

This educational style even overlapped with a period in history that made predominant use of orthographic, regular shapes for buildings. It could have been fairly simple to suppose the transference of this knowledge into the design of the frame for a building with which we were engaged in our design projects. It did not happen, in great part as we never "got that far" in the courses. So much time was spent on learning the discrete parts that the comprehensive end was never reached.

I served as a teaching assistant for these courses throughout my upper three years of this B.Arch. Professional Degree and ultimately was hired back to teach after I graduated. Being trained "in numbers" and highly respectful of the same, I continued to support the teaching of most of these courses. However, being part of a massive curricular review during the mid 1980s, took it upon myself to add two mandatory courses in Building Construction to begin to fill that large whole and begin to provide a context for the teaching of structural systems. Lectures in the historical evolution of steel and concrete systems were part of this curricular renovation. This required the removal of courses in Statistics, Calculus and Indeterminate structures and consolidating Statics and Analysis into one course. The intention was that the study of building construction and the impact of structural development on the evolution of contemporary architecture could also help students to make the bridge between the courses in “structures” and design studio.

The current slate of courses is:

- Building Construction 1 (final design project)
- Building Construction 2 (final design project)
- Introduction to Structures [compression of Statics, Strength of Materials, Analysis] (exam)
- Timber Design (exam and design project)
- Steel and Concrete Design (exam)
- Structural Design Build [chair design] (design, construction and analysis)

Fast forward 25 years and the examination of the results would conclude that materials taught in the numerically based structures course do not leave the classroom. Courses in Building Construction which are more comprehensive, looking at structural systems (in an entirely non numeric way) and enclosure systems, do influence the level of detail in design projects. This can in part be credited to the use of a design project as part of each Building Construction course that forces this integration. Design projects also provide a context for the development of the structural systems beyond the initial conceptual stages. Credible construction detailing helps the students to create more compelling and believable projects, thereby empowering them as designers.

Students continue to struggle and exhibit what could even be called hostility, regarding the numerically based structures courses that use exams for testing. They exhibit a much higher level of satisfaction in their final structures course, which is project-based and requires the design, construction and detailed analysis of a chair. Although successful as a course, this does not ultimately result in graduates who could undertake the structural design of a *building* as the complexity, materiality and subject for design is quite different.

DETAILED ABSTRACTION VERSUS PROJECT-ORIENTED COMPREHENSION:

What is revealed in this course structure is a fairly clear divide between courses that use exams and those whose evaluation method is project-oriented and context-based. Calculation-based structures courses tend to rely on exams (that are also predominantly calculation-based) for evaluation and courses in construction and design tend to use more comprehensive project-based evaluation. Project-based design work is one of the key attractions for incoming students to this field of study. Where exams are valuable for the evaluation of knowledge gained, project-based work is additionally valuable as a learning tool and aligns its pedagogy and methodology more closely to the study of design. It may come down to issues of student satisfaction and engagement, but project-based learning seems to result in the most favorable outcomes.

Project-based work also tends to be more experiential. Experiential learning has become a focus of discussion in teaching pedagogy at all levels of education. Courses that rely on more traditional teaching methods, lectures, rote memorization and simple problem solving have been criticized as not providing enough stimulation for successful learning outcomes. Within my own university experience of traditional structures courses, my favorite memory is of the creation of scaled down columns, floor systems and trusses out of balsa wood and their testing to destruction in the engineering lab.

The examination of a typical civil engineering curriculum reveals that high level, comprehensive project-based learning is does not become part of the student experience until the majority of the core structural courses have been completed. This might result in their “senior project” course being situated in their third or fourth year of a four year honors degree program. The engineering curriculum does not introduce comprehensive project design until students have enough knowledge to be able to undertake the detailed design of the entire structural system, including the sizing of members and connections. If the slate of engineering courses is compared to those taken by the architectural students, the architectural students are clearly never exposed to the same completeness or rigor and therefore not capable of undertaking such structural design, even by the end of their professional degree, given current teaching methods. The “sampler” style of truncated curriculum provides discrete parts without ever arriving at a synthesized destination. It is my contention that these courses and exercises tend to abstract the study of structures into detailed bits of knowledge that are difficult to incorporate into an architectural design problem.

LEARNING OUTCOMES AND ACCREDITATION:

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, geared to improving pass rates in the structural NCARB exams.[2] 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.” [3]

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 statement also references “contemporary” structural systems. This is a moving target and can be assumed to include current complex structures.

> “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.”[4]

If applied to the teaching of structures these also do not necessarily dictate a calculation-based methodology. “Using specific information to accomplish as task” is fairly vague. Although these criteria may vary from jurisdiction to jurisdiction, 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 both simple and complex structural systems.

What are the desired learning outcomes from structures courses? What do we want the students to be able to “do” and what do they need to be able to do to excel in this field?

THE IMPORTANCE OF MATHEMATICS:

This is not to say that mathematics and the learning of 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). There is significant belief that mathematics is beneficial exercise for the brain. Mathematics and calculation are also important in other areas of the discipline such as energy modeling and finance.

The question becomes “What is the optimal amount of numerical structures for architects?” as a function of time constraints, need and focus. There has to be enough to be meaningful and provide a solid grounding without resulting in abstract or discrete, disconnected information that can easily be seen as a waste of limited curricular time as well as a sure way to turn-off students. Calculations are useful in reinforcing learning in that they can provide memorable “proof”, but what should they be proving? This should come back to the initial question of area of focus and an understanding of what Architects need to know. This will in part look at need as it relates to the overall design of a building or structure as well as need in terms of professional practice. Both needs demand a high level of communication amongst team members. Professional need also extends to issues of liability and finance or costing.

Unlike engineering students who tend to engage comprehensive design late in their education, architecture students normally begin to design relatively complete buildings of varying scales when they enter the program. This can require at least a cursory understanding of structures and stability from day one. For these architectural students, the design of any building necessarily includes the selection of a structural system. As there is an intrinsic connection between the materiality and type of this system, and the nature of the architecture, they need to be able to differentiate between the benefits, potential and shortcomings of different system types. This includes arrangement and materiality. It does not include member sizing but rather the development of a sensibility regarding sufficiency based on observation and comparison with similar structures and types. Courses in structures should not stifle creativity or result in students "dumbing-down" their projects in fear or as the result of insufficient knowledge or skill.

> "There is some evidence that traditional engineering courses reduce the creativity of students…" Alan Holgate (Engineer/Author)[5]

This early need to be able to understand structural systems runs counter to traditional structural teaching that tends to start with statics, strength of materials and analysis and terminate in the design of the elements of very specific structural materials. If we think in terms of "just in time" delivery, students will tend to engage courses that provide information as it is needed. If early projects require an understanding of systems and stability, then perhaps the structures curriculum needs to arrange the courses and focus to provide the timely answers to these questions in order to engage the students. Structural design is an applied study. Calculations should then not be an end in themselves but a tool for learning and ideally situated in a problem that is building-related in order to have relevance.

This idea of "just in time" delivery is not new. It is, however, not widespread. "Form and Forces: Designing Efficient Expressive Structures"[6], authored by Edward Allen and published in 2009, is perhaps the only structures textbook beyond Allen's "Shaping Structures"[7], first released in 1998, that takes this approach in teaching the understanding of balance, stability, loading characteristics and material strengths by introducing the concepts and calculations within credible architectural situations – in context.

> "Each principle or equation is introduced where it is first needed, so that the student understands its role. There is no need to teach "the basics" of statics and strength of materials in advance. In fact, to do so would risk diminishing the students' interest in structural design: Numerical methods detached from their context and role in design tend to be dry at best."[8]

His approach encourages students to design their way into an appreciation of the value of calculation. Allen's texts are quite unique when compared to other structural design texts that continue to maintain the traditional "kit of parts" format and do not address complete and comprehensive design. Allen's approach and content marries calculations and free body diagrams with photos and sketches of the physical elements and construction system, which creates a very realistic and comprehensive approach to teaching. This is different from texts that may place examples of more renowned buildings alongside the lessons. The Allen text actually takes students, from the beginning, through the design of a fairly realistic structure – including addressing its materiality, construction and connections. This sort of experience can empower students at a very young stage of their education to believe that they are capable of addressing detailed structural design due to the comprehensive nature of the exercises. This avoids the problem of abstraction in the calculations that are used.

Within context, 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. These situations directly influence a better understanding of sizing and the design of elements, connections and systems. By immediately positioning the learning of structures within a specific context or applied building related situation, students can more easily relate to the need to learn this material as well as its impact on the larger issues of design.

Should architects know how to size the rebar in a reinforced concrete structure or the bolts in a steel framed connection? This is potentially too specific to be truly useful due to limitations on time as there is not likely to be sufficient time to study a wide range of situations, and most structures will require a wide range of applications. These sorts of exercises focus in too closely to a discrete part of the overall problem of structural design that by itself is quite abstract and fairly useless.

“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 to the intentions of the design. 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”.

PROBLEMS OF INCREASINGLY COMPLEX GEOMETRY:

Analytical methods for determinate frame-based structural design were largely developed in the 1800s. The 1800s was an eclectic period for design, which tended to scatter architectural studies into various camps. The 1900s began in this fashion and eventually seemed to be overtaken by the Modern Movement and International Style architecture, which settled into a predominantly rectilinear set of structural systems.[9] These sorts of structures, at least those constructed elementally or framed, like steel and timber, tend towards structural determinacy. These are easily handled through reduction into planar force problems. The majority of university level texts for architects are targeted at designing and solving framed structures. Indeterminate structures are rarely addressed.

Present calculation-based methods of teaching structures to architecture students may be proving inadequate when it comes to providing enough knowledge to undertake the detailed design simple framed-based architectural structures. How then will this enable students to undertake the design of complex structures? The development of increasingly complex structures, geometries and new materials are also proving to be challenging for the Engineers whose structural design education is more “complete”.

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 buildings 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. [10]

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 that have 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.

If abstract calculations were not beneficial or easily transferred to the simpler framed buildings of the Modern Period, then the tendency of students to design more complex 3-D shapes, empowered by their digital proficiency in 3-D modeling software, creates and even larger gap between these areas of study. Current design tendencies make traditional engineering education practices seem even less relevant and more disconnected.

DIGITAL VERSUS PHYSICAL MODELS:

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.

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. If the intended outcome of a structural design problem is to establish that the structure is stable, a physical model is better at providing the proof.

3-D BIM software such as Tekla Structures[11] has become indispensible for the construction and structural detailing industry, enabling all aspects of the design, sizing, detailing and production of shop drawings for structural systems. With the architectural curriculum still struggling to incorporate the teaching of architectural BIM, it is unlikely that such advanced structural (detailing) software will ever make its way into architectural coursework. The argument for pushing more BIM into the curriculum will however enable graduates to perhaps understand or use such software in the future.

THE EDUCATION CHALLENGE:

So this is the education challenge for the 21st century. What is the best approach for teaching “structures” to architectural students that addresses the need to enable them to design increasingly complex structures while simultaneously acknowledging the limitations of even the most comprehensive current methods (inferring Allen, Form & Forces as being at this level)? How much calculation is enough? How can we change our current methods to enable students to approach the structural design of complex structures, if even at a conceptual level. Teaching the understanding of complex structures must change to reflect complex structural design and detailing requirements.

The suggestion here is to perhaps look at the teaching of structures in terms of teaching strategies that are applied to languages. There are those who study a language very thoroughly, those who wish to converse and those who might only want to ask directions. Perhaps the way that we teach structures to architects needs to follow the middle path. This would be a path that empowers student learning by initially using a “Form & Forces” type method to properly integrate calculation and the basics of structures into a context-based set of questions. This will serve to jump-start their structures education and potentially free up some time to add other applied courses. Once this stage is set the students would be better able to take these lessons into subsequent case study work that may involve the analysis and dissection of larger complex structures with an objective of discerning “rule of thumb” type conclusions. If the former is not properly connected to the study of complex buildings, then students will continue to design these in their 3-D modeling programs, assuming that they are stable simply because they can be drawn.

AFTERWORD:

This paper argues for a pedagogical change that will bring our teaching of structures to architecture students into the 21st century.

This paper is the first part of a two part series of research papers. The second part is being presented at the ICSA Structures and Architecture Conference in Portugal in July 2013. It looks more fully at the examination of structures teaching as a language with the application of language theory and the extension of core teaching into the use of case studies.[12]

The paper is not based on empirical data or faculty and student surveys. These might follow. The hope is to initiate a discussion that in turn might lead to some teaching exchange and experimentation. Some of the most interesting and effective curricular changes can happen in this way.

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.

Endnotes

1 School of Architecture, University of Waterloo.

2 NCARB ARE Pass Rates http://www.ncarb.org/are/are-pass-rates/divisionpr.aspx

3 NAAB 2009 Conditions for Accreditation. http://www.naab.org/accreditation/2009_Conditions.aspx

4 NAAB 2009 Conditions for Accreditation. http://www.naab.org/accreditation/2009_Conditions.aspx

5 Allen, Edward and Waclaw Zalewski. “Form and Forces: Designing Efficient, Expressive Structures”. John Wiley & Sons, Inc., 2009. P. xiii

6 Allen. Form & Forces. p. xiii.

7 Allen, Edward. “Shaping Structures”. John Wiley & Sons, Inc., 1998.

8 Allen. Form & Forces. p. xiii

9 This would exclude some of the work of Wright, Nervi and Saarinen which the author acknowledges looks at many curvilinear and potentially indeterminate type structures.

10 The exceptions would be Gaudi and Nervi whose engineering backgrounds and unusual daring resulted in very experimental and unusual geometries.

11 Tekla Structures is Building Information Modeling (BIM) software that enables the creation and management of accurately detailed, highly constructable 3-D structural models regardless of material or structural complexity. Tekla models can be used to cover the entire building process from conceptual design to fabrication, erection and construction management. http://www.tekla.com/international/products/tekla-structures/Pages/Default.aspx

12 Boake, Terri Meyer. The Dynamic Phraseology of Structures: Enabling the Design of Complex Systems. ICSA Conference 2013. www.tboake.com/bio/phrase-final-paper.pdf