Spatial Cognition Support for the Mechanics of Building Design: Explorative Learning of Design Principles through Three-dimensional Models of Structural Behavior

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Abstract: A web-based tool for visualizing the simulated structural behavior of spatial building models was developed to better support the teaching of structural design to both architects and engineers. The main didactic issues involved establishing a consistent and complete three-dimensional vocabulary throughout a base collection of structural system diagrams that is as related to familiar 2D conventions and as intuitively "legible" for architecture students as possible. To this end, the visualization techniques used in a number of structural simulation programs for engineers were assessed according to didactic criteria in the context of the architecture curriculum at two levels: semantic initial assessment for preliminary user-interface design and explorative learning effectiveness based on an implementation of the developed prototype. The results suggest generalized criteria for the modeling of constructivist learning resources for higher education in the architecture, engineering, and construction (AEC) domain.

1. Introduction

The three professional fields comprising the "AEC domain" – architecture, engineering, and construction – are closely related in practice by virtue of their common focus on the built environment. Yet there are fundamental differences in the respective working methods and immediate design concerns of each field, which are reflected in distinct styles of academic training.

Spatial thinking and modeling skills are central to the qualification of architects, whose education traditionally revolves around simulating the building design process in the form of so-called "design studios." Comprising over half of the curriculum in typical architecture programs, such studio teaching is inherently constructivist in approach, engaging students in the three-dimensional modeling of physical relationships – the outward shape – as a means of grasping and developing complex solutions to building design tasks. In contrast, classic training of civil engineers focuses on describing the quantitative relationships between mechanical and material properties ("working with the numbers"); qualitative geometric and time-dependant patterns are of secondary concern in reaching a design solution. Both these "angles on the building" are, of course, closely interdependent views on facets of the same physical construction in space and time.

With an aim to better bridge this design-concern gap between architecture and engineering, our e-learning development work focuses on the interdisciplinary subject matter of advanced structural design and construction methods, and builds on a strong foundation of computer skills that both architecture and engineering students bring to their studies. Given the fact that nearly all AEC students at the authors' university are computer literate, electronically well-equipped, media savvy and highly motivated to employ sophisticated digital means in their everyday learning work, an integrated project titled "*archistructura*: Knowledge Construction Site for Building Science and Structural Design" has been initiated to encompass the following three main application areas: *design aids* – design support for architects and engineers, *study aids* – courseware and accompanying learning resources, as well as *buildings* – a database of documented design precedents with integrated case studies (Jaksch & Rudy 2005). Working versions of the various components are being provided to students in a web-publishing framework on a running basis, targeting content needs as they arise in conjunction with the current curriculum for both architecture and engineering programs (Pfeiffer-Rudy & Jaksch 2004) [1].

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[1] General *archistructura* URL: *http://www.archistructura.net* (English and German); see also embedded version in department website (with access to extended student resources): *http://www.iti.tuwien.ac.at*.

The following paper reports on a recent, substantial enhancement to the *study aid* applications of *archistructura*: the tool “3D Visualiser,” as a standalone application or web-based embedded applet, for visualizing the mechanical properties of three-dimensional simulation models through learner-driven exploration of their structural behavior.

2. Didactic Approaches to Structural Design for Architects

The largely engineering-based subject matter behind structural design, statics and strength of materials, is generally quite unpopular with architects, a “necessary evil” that is often viewed as more likely to hamper their creativity than to improve the quality of what they should be learning to design competently: buildings with a projected physical reality beyond the digital visualization, subject to physical forces (“loads” such as gravity, wind and weather, etc.) that may or may not immediately impact formal qualities (psychological effect). The architectural fascination is further limited by the simple fact that well-engineered structures aim to be as geometrically static as possible, in equilibrium with the forces acting upon them over a decidedly long period of time (design lifecycle of 50+ years, i.e. spanning generations). Nonetheless, understanding the principles of mechanical behavior is essential to designing buildings that shall actually one day remain standing and appreciated in the real world (cf., Alexander 1979), so fostering students’ natural curiosity by bringing such invisible phenomena to the fore of their visual cognition should be the principle objective of new learning resources in this area.

A look at what architecture students “bring to the table” reveals a discrepancy in comprehension levels between spatial and mathematical cognition, which is often neglected in the teaching of basic mechanics aimed at building design. In a manner more appropriate for engineering candidates, the calculation methods for statics and strength of materials are presented incrementally in a sequence of increasing mathematical complexity, meaning the concepts presented first are those that can be most simply described in fundamental equations. Other, more advanced concepts are not addressed until the math can follow suit – too late for most architects (whose math prerequisites are relatively minimal), with the result that the cognitive connection between structural behavior and design relevance is hardly achieved before the boredom sets in and all interest in the integral subject matter is lost for good.

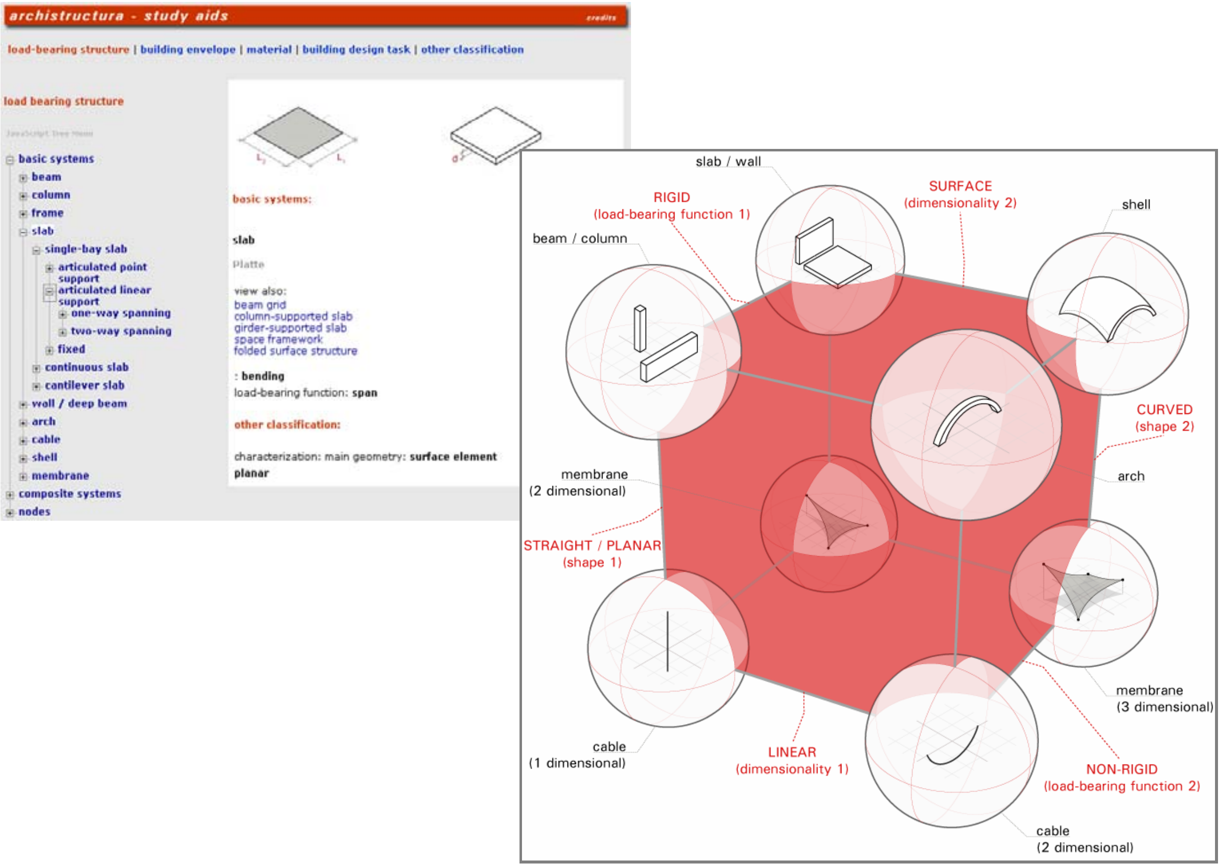
Though not necessarily fluent in reading mathematical equations, architecture students do, however, show highly developed skills in recognizing spatial patterns and reasoning by analogy across multiple dimensions (Rudy 2005). It makes sense to use these skills at an introductory level, as a point of entry to understanding where and how the math may be necessary to get the “hard numbers” needed when developing a building design to “construction-ready” maturity. Even if architects rarely calculate such numbers themselves in practice, it’s important to understand what, exactly, the structural engineer contributes and how both sides of the design process can communicate better on the way to an improved realized result in the built environment we all share.

2.1 Establishing the Universe of Discourse

When talking about long-standing teaching traditions in the AEC domain, a “literal” understanding of modern learning philosophies (such as constructivist approach, scaffolding, etc.) becomes quite apparent: the distinction between the object of study (building design task as learning object) and the cognitive process of studying it blurs to the point where a metaphorical usage of the cognitive learning terminology can hardly be distinguished from its literal application. This is to say that much of what has been tested and proven in the education of architects and engineers may, indeed, serve well in other domains by analogy, much like the architecturally grounded “pattern language” of Christopher Alexander (et al. 1977) has found its greatest impact in informatics and artificial intelligence, outside of the architecture profession. In order for others to better draw valid analogies, we must first spell out the semantic foundation of our originating arena, that is, the nature and morphology of building structures. This process of establishing the terminology in a field of reference, a common ground for talking about the inherently non-verbal “things” instructors try to convey to their students, is also fundamental to a solid didactic approach for teaching principles of structural design to architects.

Structural taxonomies and descriptive models based on morphological characteristics are very useful as a point of departure for drawing analogies at an abstract, pattern-based level that both architects and engineers can relate to (cf., Büttner & Hampe 1985, Engel 1997). Such a disciplined hierarchical vocabulary, which has been developed and refined over the years as metadata to organize building design resources, constitutes our *universe of discourse*, that is, the set which, with reference to our particular context, contains all possible elements having the same characteristics and from which sets can be formed (cf., Rajasekaran & V. Pai 2004). It implicitly contains a substantial amount of essential structural information, knowledge that is shared with students in the form of so-called “pictionaries” (Fig. 1) and accompanying explorative resources.

With the aim of internationalizing as much *archistructura* content as possible, the pictionaries are currently being generated and presented in both German and English versions. Of course, a number of the original German expressions cannot be exactly matched to equivalent expressions in other languages, which inherently makes such unified taxonomies less “natural” than they would be if kept within the semantics of a single spoken language. Such linguistic discrepancies are visually resolved to a certain extent through the hierarchical structure of the terminology and other non-verbal information contained in supporting media (such as icons, movies, and models). Beyond the taxonomic representation, the characterizing sets of terms can also be expressed mathematically (crisp sets of tuples), as well as diagrammed with a theoretically unlimited number of semantic dimensions (*k*-cubes, cf., Bondy & Murty 1976). Given the spatial understanding of building designers, it makes cognitive sense to support the interpretation of up to three dimensions by visual analogy to the x/y/z/-coordinates of space (Fig. 1). Correlative comparisons of different buildings with similar formal characteristics and recurring structural features can thus reveal generalized relationships between architectural and structural principles (Rudy 2005).



basic systems:

slab

Platte

view also:
beam grid
column-supported slab
girder-supported slab
space framework
folded surface structure

: bending
load-bearing function: span

other classification:

characterization: main geometry: surface element
planar

Figure 1: Screenshot of the “pictionary” for load-bearing structural systems in *archistructura* and the underlying morphological characterization of structural components in a *k*-cube.

2.2 Graphic Conventions in Architecture and Engineering

The graphic standards and conventions familiar to architects (cf., Ramsey et al. 2000) were established primarily to convey relationships between spaces and outward shapes at the global level (floor plans, sections, elevations), as well as between materials configured to separate spaces at the detail level (construction details). By comparison, diagrams relating the mechanical properties of a building’s load-bearing components (e.g., the system diagram of a static calculation model or finite element analysis of material stress patterns) are considerably more abstract and not as immediately accessible to the architecturally trained eye (Fig. 2).

Translating the *universe of discourse* described above into symbolic representations led to the development of a three-dimensional graphic vocabulary for rendering a structural model in semantic terms common to both mechanical (engineering) and morphological (architectural) understandings of structural behavior. Referred to as the “function model,” it conveys structural components by their most characteristic (generic) role in the overall context of typical load-bearing configurations. This information is what actually “explains” the structure and is, therefore, particularly valuable for didactic purposes (Fig. 2). Since such terms are not originally contained in the data sets comprising mechanical simulation models, they must be added in a separate stage of instructional enhancement.

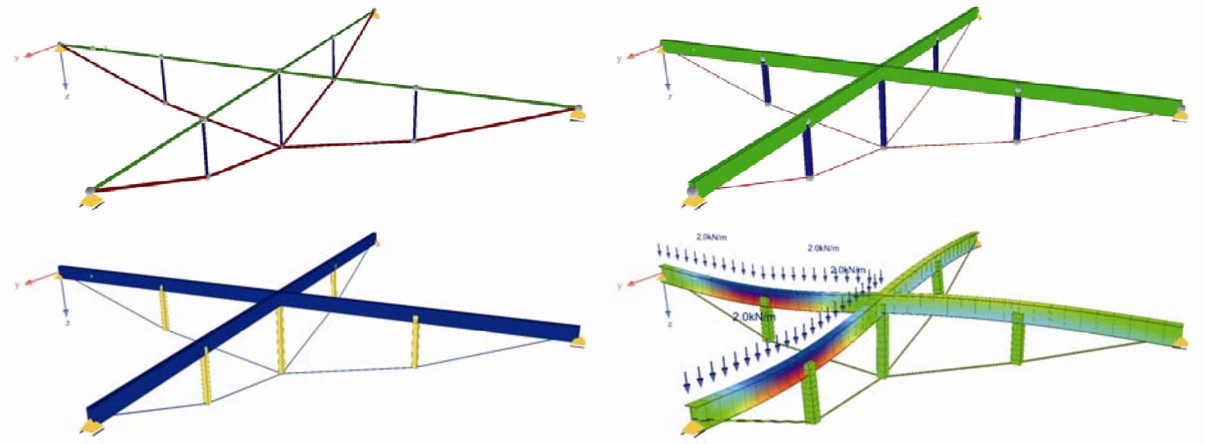


Figure 2: Four different views of the same structural behavior model – *system* (static calculation model), *function* (semantic definition of elements in generic terms), *design* (material and geometry) without loads and with stress texture (load case with deformed geometry).

Particular difficulties are posed by the problem of characterizing the nodes of simulation models using graphic symbols, which must carry a highly complex set of mechanical information in a relatively small region of the visualization. Especially the specification of bearing nodes in all six degrees of freedom is of critical importance to the overall structural behavior of the simulation model and should be related as faithfully and completely as possible. A comparative analysis of graphic engineering standards (cf., EUROCODE) and a wide variety of simulation programs showed that, at present, no consistent concepts exist for rendering bearing nodes in spatial visualizations. Our proposal is a compromise: the conventions for symbolizing nodes in pairs of two-dimensional diagrams are combined orthogonally (Fig. 3), whereby two degrees of freedom are sacrificed for the sake of visual simplicity (the "missing" information can still be revealed in a separate detailed description of the node properties). Specialized rendering forms can be used to graphically integrate more node information, but these are generally difficult to read and may obscure more than they illuminate at the first stages of comprehending a simulation model.

Figure 3: A complex support situation visualized as the bearing node of a structural behavior model – standard 2D view set and alternative 3D views (simplified and specialized proposals).

"And finally, the things which seem like elements dissolve, and leave a fabric of relationships behind which is the stuff that actually repeats itself, and gives the structure to a building ..." (Alexander 1979, 89)

3. Development of a 3D Visualization Tool

The experiences gained in teaching structural design to architecture students determined the need for a tool that makes what is mechanically invisible and static, visible and dynamic, by activating a sense of both time and space in cognitive exploration (cf., Gershon 1994). Competing visualization concepts were initially developed and tested in the context of an introductory course in structural design (see below), and later validated in the framework of a set of advanced courses in structural logic targeting both architects and engineers (see next section: "Evaluation of Effectiveness and Usability"). Aside from programming the concrete visualization tool, it was also necessary to develop a consistent base collection of simulation models, i.e. create the actual content to be viewed and tested, hand-in-hand with the user-interface design. At present, 67 basic systems and 18 composite systems, as well as preliminary versions of approximately 50 "real-world" building models are available as a foundation for using the so-called "3D Visualiser."

3.1 Initial Learner Assessment

The first level of assessment focused on establishing a graphic vocabulary for the semantic terms used to explain building structures at the introductory level. In the process of registering for the compulsory course “Structural Design” (approximately in the middle of the core curriculum for the architecture program), students were required to fill out an online questionnaire asking them to a) identify six three-dimensionally represented structural elements by selecting an appropriate term for each from a drop-down list and b) select the more “understandable” representation (from a choice of two) for three different, increasingly complex structural bearing situations.

The restricted vocabulary provided in the drop-down list for the first part had been defined to enable the combined testing of two didactic aspects: correctness of element recognition and preferred terminology. For each displayed element, there were at least three essentially correct answers available in the list, which contained near synonyms from three related semantic sub-domains (“world views”): *mechanical*, *structural*, and *architectural* (Fig. 4). It should be noted here that the structural sub-domain, which communicates functional characteristics as described in the previous section, can be expressed compactly in German with common terminology that is clearly distinct from the mechanical and architectural sub-domains. The same tripartite distinction does not, however, translate directly into entirely equivalent sets of English terms (architectural terminology is generally used when talking about structural design in English).

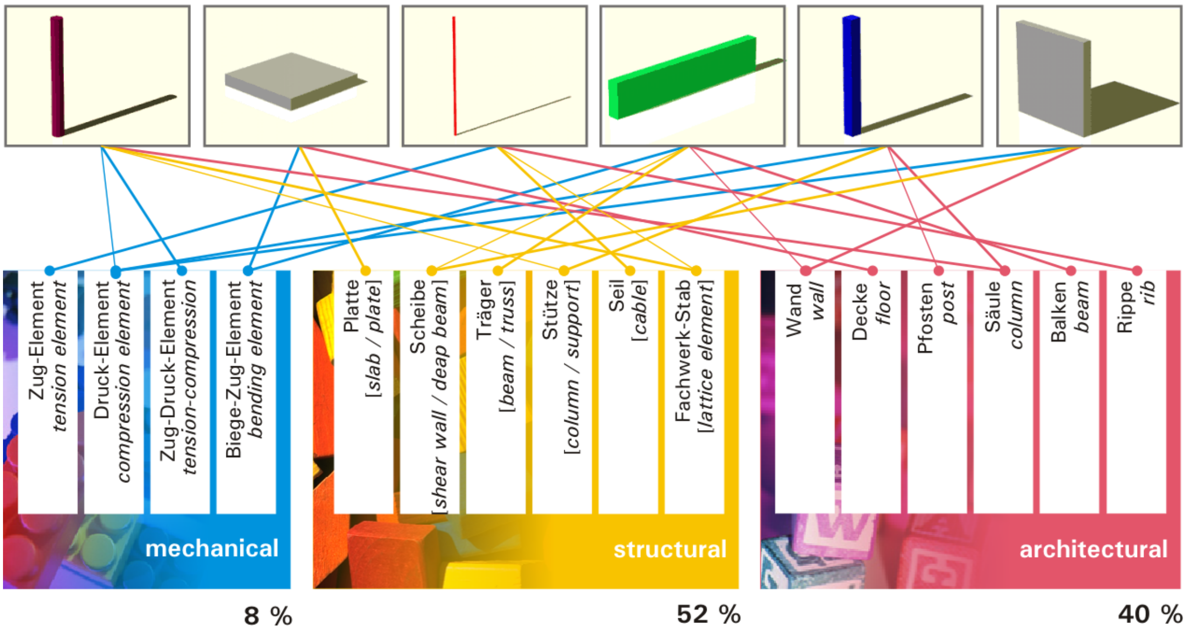


Figure 4: Restricted vocabulary to identify a series of simple structural elements, classified by semantic domain (assessment results in percentage of responses for each domain).

In total, 378 students (188 females and 190 males) participated in the assessment at the beginning of the project in 2004. Beyond helping us establish “where the students were coming from” verbally on their way into their first major compulsory course in structural design, the results of the poll were used to fine-tune the geometric proportions of generic representations to improve the clarity of function model visualizations, especially in those instances where the initially proposed representations were consistently misread across semantic sub-domains. Surprisingly to the authors, significant gender differences in comprehension could be ruled out with respect to both the preferred terminology and the ability to read 3D representations in structural terms.

3.2 Interface Design and Implementation Considerations

Since the visualization tool is aimed at a wide range of target users, the technical side of the project required technologies that operate on different platforms and ensure web-based applicability in subsequent programming generations. As an intermediate format, the extensible mark-up language (XML) was chosen for structuring model data because it is especially flexible, well-suited for a number of well-documented reasons (Davies et al. 2003), and can be expected to remain a viable format for some time to come in the future. To maximize compatibility with different platforms, it was decided to program the software in the object-oriented language Java with its cross-platform “virtual machine” concept and make use of a number of related technologies that work within this environment (e.g., Java-Swing for graphical user interfaces, Java3D to visualize three dimensional scenes, or JDom for interacting with XML-files) [2].

Based on the preceding conceptual analysis, a prototypical user-interface was developed and implemented with the following sets of toolbars organized around the main model window (Fig. 5):

- selection of the model type to be viewed (*design*, *system*, or *function*), the color-coding scheme for the model surfaces (*material*, *stress/force*, *function*, or no textures) and basic rendering options (solid or wire frame, coordinate axes, etc.);
- toggling and relative scaling of system nodes symbols, load vectors, displacement and animation (visual exaggeration of the deformation);
- navigation buttons for panning, zooming, rotating, and “homing” (right-adjusting) the current view.

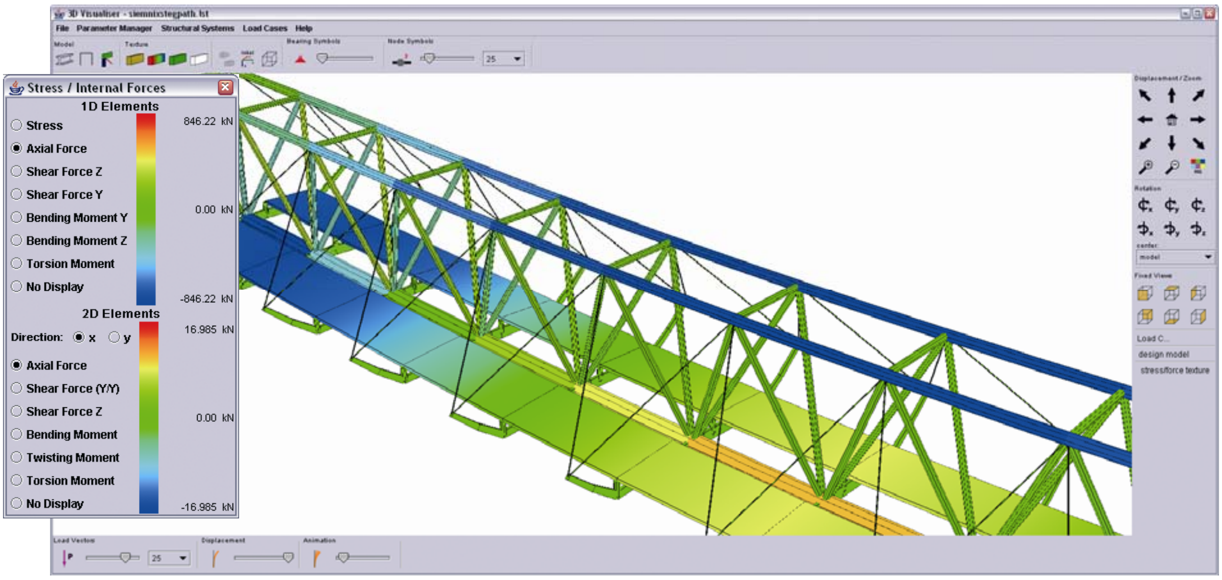


Figure 5: Screen shot of the user interface – design model view of a deformed bridge structure (color-coded texture options to reveal facets of mechanical behavior).

Models can also be manipulated directly in the main window using standard drag-and-drop mouse functions. Popup dialogs appear wherever needed for immediately specifying view details, such as the selection of which stress/force texture should be displayed (with associated color scales in the legend, Fig. 5). In extension to the embedded applet version of *3D Visualiser*, the standalone application includes a menu bar at the top for accessing functions needed to navigate locally stored collections of simulation models offline (*File*, *Structural Systems*, and *Load Cases* [3]). Finally, the language can easily be switched by selecting one of the integrated XML-based language sets, as well as values for a range of further view configuration parameters saved and managed as reusable settings in XML format (*Parameter Manager*).

4. Evaluation of Effectiveness and Usability

Once the first versions of the *3D Visualiser* had been programmed and informally tested by the developers, a number of working hypotheses that had been assumed up to this point needed to be validated by “real users,” that is, by members of the target audience of structural design students it had been designed for. As with all entirely voluntary assessments in an academic setting, the motivation of students to participate in an engaged fashion is limited and the results are hardly representative of typical software use. Moreover, the information yielded to developers by such “no-budget” experiments is generally anecdotal and rarely provides evidence of how – or even whether – students intellectually process the knowledge provided to them through the new learning resource.

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[2] More about XML, Java, and related web-based technologies: *http://www.w3.org/XML/*, *http://java.sun.com/*, *http://java.sun.com/docs/books/tutorial/uiswing/*, *http://java.sun.com/products/java-media/3D/index.jsp*, *http://www.jdom.org*.

[3] Applied boundary conditions are selected in the applet version (without a menu) from a drop-down list of simulated load cases below the main window.

Fortunately, we were able to find a meaningful occasion (i.e. a suitable curricular setting) for enlisting a group of two dozen representative students, who were willing and able to work with *3D Visualiser* to explore the base collection of simulation models and receive credit for a course in advanced structural systems. Instead of writing a regular examination to complete the course, these architecture students were ask to perform a "structural system study" in the form of an online questionnaire with embedded learning resources. The questions were designed to activate immediate use of the visualization tool in combination with other supporting *archistructura* resources (pictionaries, building collection), both in the applet version online and as an offline application.

The learning goals were assessed in six sets of comprehension questions corresponding to increasing levels of cognitive complexity (Fig. 6): comparison of basic systems under vertical and horizontal loads (3 questions each), recognition of subordinate and superordinate structural concepts in composite systems (2 questions each), and, finally, direct and analogue recognition of building structures in the "real world" on the basis of 4 structural simulation models corresponding to buildings published in the *archistructura* collection (Fig. 7). Extended technical and editorial feedback was informally encouraged by providing free-form comment fields in association with each section of the questionnaire.

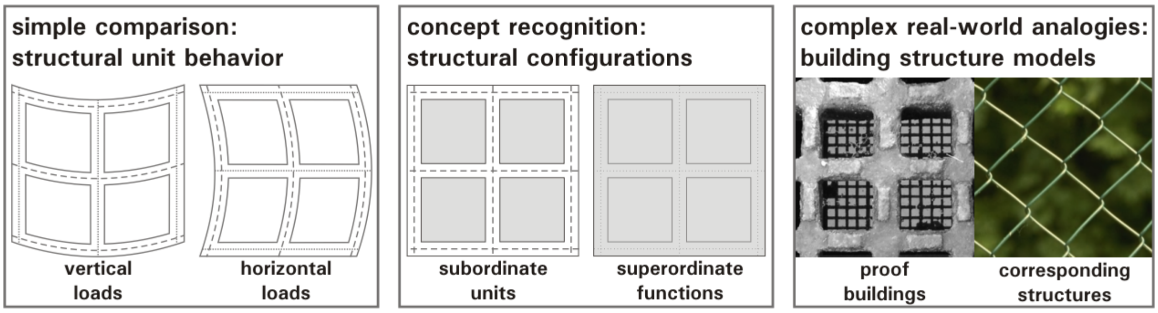

Figure 6: Comprehension assessment of load-bearing structural behavior – six sets of questions corresponding to three cognitive stages of visual perception.

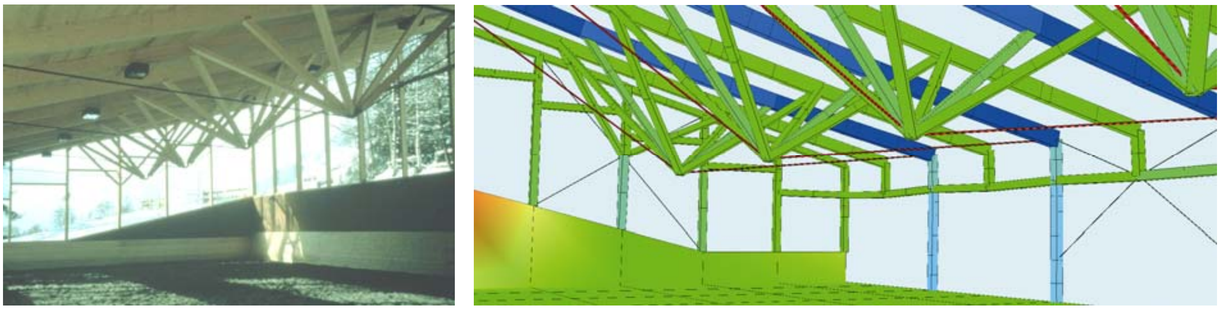

Figure 7: Simulation modeling of real-world building structures – indoor riding arena in St. Gerold, Austria (case study and preliminary model: E.M. Streit; structural simulation model: S. Jaksch).

At the end of the study, students were asked to summarily evaluate a series of usability aspects on a scale of 1 to 5 (with 1 = best mark). The results clearly showed a strong need to improve the performance and stability of the software (grades ranging from 2 to 4). Overall impression, ease of installation, clarity of user-interface, and the like were generally graded higher (1-3). The last question – "learning effect of exploring 3D simulation models" – received the highest marks overall (1-2), and most of the comments, though critical of technical details, lauded the visualization tool as a highly effective learning resource: a positive subjective impression that is objectively corroborated by the largely correct and thoughtful answers given to the comprehension questions.

5. Summary and Prospects

The spatial visualization tool that we set out to develop at the beginning of the project has, at this stage of development, proven to be even more successful than originally expected as a means for architecture students to gain a deeper understanding of structural design principles by exploring the mechanical behavior of simulation models. Intensifying the application in the training of civil engineers promises to yield findings that can significantly promote the common language needed to cooperate more effectively in the AEC domain, both educationally and professionally.

A range of functional extensions and additional features are awaiting their realization. At present, in experimental form, the functionality has been expanded to allow input that enhances the base models semantically (pick and editing tools). As such, the *3D Visualiser* already functions as editorial support for adding attributes to existing structural models by coupling the semantic modeling layers with ontological descriptions stemming from other applications. A base collection of models is also serving as parametric templates for a range of common structural systems (beams, frames, arches, etc.) that are used to dynamically generate input files for an engineering-based structural analysis program. Recent developments include interactive mechanisms for combining such component models in a manner that enables model generation and explorative simulation of more complex building structures "on the fly" (Jaksch & Rudy 2005).

With respect to future improvements, it became apparent in the course of programming and evaluation that a more efficient data structure than the XML standard is necessary to optimize and stabilize the software in order to make the handling of larger and more complex structural models technically feasible. Once a statistically relevant collection of manageable models has been established, a long-term goal will be to distill and translate their "grammatical rules" into machine-readable parameters, thereby creating semantically "self-aware" components for integration in the kinds of fuzzy-set search operations (cf., Zadeh 1987, Klir & Yuan 1995, Rajasekaran & V. Pai 2004) needed to guide multi-faceted decisions in the building design process.

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