Digital Database of Building Structural Systems: an Educational Tool to Support Multi-disciplinarity and Enrich Design Vocabulary in Preliminary Conceptual Structural Design

Application in Long-span Structures

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Abstract. In building design practice, especially in the preliminary stages, multi-disciplinarity is often ignored, due to the intrinsic characteristics of the design process, the features of design education, or lack of appropriate tools, resulting in a limited design vocabulary. This paper investigates the development of a digital multi-media database of building structures, operating as a supporting tool in preliminary structural design in order to enrich and justify design decisions. The proposed database responds to the need of bridging the gap between systematic, yet abstract, theoretical analytical approach of structural systems and descriptive, visual, yet fragmented, representations of architectural forms, through a highly visual, yet thoroughly systematic, approach based on case-studies.

Keywords: Database: multi-disciplinarity; structural design; digital library; conceptual design.

Multi-disciplinarity in preliminary structural design: drawbacks and challenges

Building design is a complex process, involving several disciplines and balancing numerous parameters related with intrinsic design investigations or exterior social, economical and technical factors. Functional, morphological, structural and detailing features, as well as issues related to the design and construction process, interact to define the final result. The choice of structural system and consequent design of the structure is an important design parameter, preliminary structural design decisions having an immediate impact on the structural and material characteristics of the project.

Contemporary design possibilities consist of a wide range of structural systems and technologies, the design process becoming more complex
and demanding in terms of knowledge, experience and involved disciplines. Especially in the case of special structures, such as high-rise or long-span building structures that require particular technical solutions and differentiated design and construction methods, structural design issues become of critical importance, therefore of increasing interest for the designer.

Historically, some of the most remarkable building projects have been the outcome of practices with an enhanced degree of inter-disciplinarity; cases of varying type of inter-disiplinarity based on the educational or knowledge background, on individual study and creative sense, on teamwork and on-site expertise. These notable cases extend from the architect of classical antiquity with the wide knowledge range and the renaissance architect with the overall control of the building process, to the industrial revolution engineer with the high level of expertise in large-scale technical projects (G.Eiffel), the structural engineer with a concrete theoretical background and significant sense of creativity (F.Candela, P.L.Nervi), the single designer with a multiple educational background (S.Calatrava) or multi-disciplinary design practices with innovative proposals (R.Piano, R.Rogers, P.Rice).

In practice though, multi-disciplinarity in preliminary design is quite limited, while initial morphological, structural and construction decisions are based on individual knowledge, experience or intuition instead of examining the range of possible solutions in a systematic and profound way.

Issues related to the intrinsic characteristics of the design process (wide range of choices and parameters, subjectivity, lack of experience, limited time and resources in preliminary stages, separation of fields of expertise, allocation and isolation of tasks), the features of design education (segregation of knowledge fields and technical specialization, analytical vs. synthetic approach, quantitative vs. qualitative methods) and the related methods and tools (with poor inter-disciplinary features, emphasizing on analytical tasks, used primarily for computation or representation purposes) discourage multi-disciplinarity and hold back the preliminary structural design process, thus constraining the design vocabulary, especially in the case of special structures.

Textbooks and bibliographical references on building structures express two different modes. A systematic, yet abstract, theoretical approach of structural systems is performed with analytical quantitative terms, while the architectural form, especially when referring to morphological, functional, aesthetic and material characteristics, is approached in a descriptive, general, yet highly comprehensible, way based on conceptual or representation morphogenesis terms.

The information is hardly related to other scientific fields, resulting in limited visualization possibilities and inadequate conceptual understanding of the structural behavior of building components, therefore restricting structural design capabilities and multi-disciplinary perspective. (Molyneaux, Setunge, Gravina and Sie, 2006)

**Supporting tools for preliminary structural design**

“Preliminary design is rarely discussed in detail in textbooks on structural design, most on which tend to concentrate on the structural analysis and design of individual components, such as beams and columns, with little reference to their function in the overall structure.”(Harty and Danaher, 1995)

Approximate methods for initial selection and sizing of the structural system are primarily used in this stage. Aiding tools consisting of charts and tables (Figure 1), carry to the design table technical expertise and rules of thumb “based on generalizations made from a large set of examples which were produced using sound engineering calculations.” (Harty and Danaher, 1995) These charts and tables for different types of structures have limited applicability though, due to the difficulty to collect and consolidate all this information, generally not available in the form of handbooks, but spread over many small reports. (Ravi and Bedard, 1993)
Developing a digital database of building structures as a multi-disciplinary tool in preliminary conceptual structural design

Relevant research
In structural engineering, several attempts have been done towards the development of methods and tools for the preliminary structural design.

At first, computers were used to solve mathematically well-defined structural analysis problems. It was not until the introduction of artificial intelligence in the 1960s that attention was given to the more open-ended problems of design. Even so, algorithms were only able to concentrate on areas with well-defined rules, such as detailed design.

The emergence of knowledge-based expert systems (KBESs) in the 1970s intended to provide support for engineering design, beyond drafting and computation, allowing designers to draw on heuristic knowledge acquired from textbooks, standards, and engineering experience. Examples of expert systems in structural design are presented in various cases (HI-RISE, Tall-D, DOLMEN, SSE). Advanced optimization techniques were implemented to deal with drawbacks of rule-based KBESs, such as limited practicality when developing individual or new design solutions and difficulty to expand once the knowledge base is defined. Artificial intelligence methodologies, such as analogical reasoning, could give solutions to new problems using knowledge from previously solved problems with similar aspects. (Harty and Danaher, 1997)

Adaptive search techniques known as genetic algorithms have extended the evolutionary approach to conceptual building design. Decision support systems for conceptual building design were developed to investigate concurrently designs that use different configurations, construction methods and materials, introducing concepts of parametric design. Incorporation of graphical user interface and object oriented programming tools within these systems allowed flexibility, robustness, and extensive user interaction at various levels. (Rafiq, Mathews and Bullock, 2003)
Concepts and mechanisms of Darwinian evolution and natural selection are currently incorporated in evolutionary algorithms. Evolutionary Computation is an optimization process allowing for integration of conceptual and detailed design processes and, even, eliminating the human designer from the loop, while the evaluation and selection of design concepts are automated. (Kicinger, Arciszewski, De Jong, 2005)

Among the few general purpose computer-based tools to assist structural designers in synthesizing structural configurations, SEED (Software Environment to Support the Early phases in building Design) is a characteristic multi-disciplinary project developed at Carnegie Mellon University (1992-2005) intended to provide computer support for the conceptual design of buildings. Motivated by the
designer’s need to explore a wider range of feasible alternatives and the wish for multi-disciplinary approach, the emphasis is on supporting early design exploration, that is, the fast generation of alternative design concepts and their rapid evaluation against a broad spectrum of relevant – and possibly conflicting – criteria. “(Rivard and Fenves, 2000)

The system makes use of two mechanisms that encapsulate the engineers structural knowledge providing the ability to generate and explore a much wider range of alternative structural solutions for a given task as well as to reuse previous knowledge: A hierarchically structured, yet customizable, technology library complemented by individually created case libraries, is providing the toolkit of potential alternatives, while case-based reasoning, an artificial intelligence methodology, allows designers to save solutions as a natural by-product of the design process and retrieve them in later ‘similar’ design situations to adapt them to the new situation. Even so, “SEED software environment is not intended to be universal. It is unlikely to contain a wide range of technologies for ultrahigh or extremely large-span buildings. Rather, it is intended to assist in the design of recurring building types.” (Fenves, Rivard, Gomez and Chiou, 1995)

**Methodological approach**

Historic examples and current research are pointing towards a multi-disciplinary design approach. Enhancing creative potential in professional and academic practice is possible by building scientific cross-disciplines and developing inter-disciplinary methods and tools. Introducing such tools in the preliminary design stages can be of major importance for the effectiveness and efficiency of the design process.

The scope and need for such tools in the process of selecting and designing the structural system, could be questionable as it may produce automated solutions or result in sterile reproduction of existing configurations, isolating the outcome from the design context. While these concerns are reasonable, it is obvious that such tools could have a powerful decision-supporting role for the designer, structural engineer or architect, if used in preliminary design as a starting point based on a library of case-studies of similar scale, function and context, in analogy to methodologies implemented in numerous architectural analysis or synthesis courses.

By focusing on comparative methods, enhancing analytical capabilities and substituting for experience, this approach emphasizes on qualitative techniques aiming to a comprehensive understanding of structural behavior and to the development of structural intuition, while encouraging multi-disciplinarity through common tools. (figures 2, 3)

In the current context, where new interest in tectonic culture, in materiality, in manufacturing processes and production systems is rising, the application of new technologies for archiving, educational or research purposes could be of critical importance, introducing innovative teaching and research possibilities in the building structures design studies.

*Figure 2*

Structural diagrams as a representation tool for studying and communicating structural configurations of buildings (student project: A.Apostolou, D.Paraskeua, N.Stamoulidis, Un.of Thessaly, 2004)
Digital tools can be the means towards the development of a database as an inclusive information management tool allowing for systematic collection and flexible retrieval of data.

Several examples of digital databases regarding building structures, usually with static, 2D content, are currently available on-line (STRUCTURAE, VITRUVIO, GREAT BUILDINGS,...) from professional, private or academic institutions.

In a systematic effort to link content, knowledge and learning, European Commission has launched 'Digital Libraries and Content' initiative to promote research projects “making content and knowledge abundant, accessible, interactive and usable over time by humans and machines alike. Digital libraries are organized collections of digital content made available to the public in order to develop cultural assets and reinforce creative potential.” (Information Society and Media, 2006)

In this direction, a content specific application is the Architectural Archives action, part of the European project GAUDI (Governance, Architecture and Urbanisme: a Democratic Interaction): a research initiative that has brought together a group of European institutions managing architectural archives and has resulted in the creation of a documentary and information resource portal (www.architecturearchives.net: 2004) on archives for use by architecture firms.

More elaborate academic applications of digital databases in engineering fields include a couple of characteristic cases from the National Technical University of Athens, Greece. ‘Limenoskopion’ by the Department of Civil Engineering (N.T.U.A., 2007) focusing on ports of ancient Greece and ‘Built Memory’ by the School of Architecture (N.T.U.A., 2005) focusing on historical traditional construction systems, methods and technologies in Greece.

In an academic multi-disciplinary context, this paper investigates the development of a digital database of structural systems to be used as a supporting educational tool in preliminary architectural design, especially in the case of long-span structures. The database being the tool, new technologies would be used for information management purposes, while the methodological approach would be based on case-based reasoning.

“Case-based reasoning is an analogical reasoning method that uses previously stored solutions as a means to solve a new problem, to warn of possible failures, and to interpret a situation. These cases can be used as sources of inspiration, or as drafts on the
basis of which a more relevant solution to the current problem can be developed.” (Fenves, Rivard, Gomez and Chiou, 1995)

In a multi-disciplinary research context, the project enhances a systematic analytical recording of building structural systems. In an educational level, it enriches the knowledge background and the methodological tools developing information management and communication skills. From the design point of view, it reinforces creativity by enriching and justifying design decisions and re-introducing structural, technical and material choices as crucial design parameters.

**Structure of the database**

‘Building Structures’ is a digital multi-media database of building structural systems. The database provides a full range of data about the characteristics of each project (geometrical, structural, material and technical), as well as information about the design parameters (function, place, time, cost, design and construction process, conditions,…). Data includes structural and technical information (general layout and structural configuration, structural system category, geometrical characteristics of structural elements, construction method) in several levels (structural system, structural subsystem, structural part, node). (figures 4, 5)

The development of the database is based on a hierarchically structured system. Building structures are analyzed and described in a tree-like development, while structural parts are defined and analyzed in subsequent levels.

In the initial phase, data input, in terms of form and content, is centrally controlled; so is the overall hierarchical structure. The system is flexible, capable of incorporating new data, new additions to existing data or new associations, by changing the width or depth of the analytical descriptions. Retrieval and use of data is open and can be performed in different levels, allowing for different possibilities of entry or routes within the system. Vertical navigation within the same structural entity or horizontal navigation by associating elements of the same level is possible.

In an advanced version, a system containing information based on topological associations and navigated with appropriate artificial intelligence methods could develop capabilities of retrieving or producing subsets of possible solutions responding to certain values of parameters, thus introducing parametric design possibilities.

**Application: long-span building structures**

Data is collected, analyzed, produced and organized within the framework of building technology courses in an undergraduate architecture curriculum, emphasizing on case-studies with special characteristics (lightweight, long-span or demountable structures,…). In the case of international projects, information is collected from bibliographical references, while original material is searched for when Greek projects are studied. The development of the software environment is expected to take place under an academic research grant.

Use of the material is evidenced on an experimental basis in architectural design courses with projects of special requirements (e.g. airport) (figure 6). Knowledge of relevant structural, construction and technical issues is limited, so is experience and related references, while bibliography and textbooks focus either on morphological and functional approaches or abstract theoretical structural analysis.
This material constitutes an anthology of case-studies, containing structural and technical information along with design parameters for each project. This digital library operates as a supporting tool in the selection of structural system, material and construction solution, while providing input for initial sizing through analogical approaches and comparative methods.

**Future development: remarks, potential and concerns**

Issues related to the tool (database), the methodological approach (case-based reasoning) and the medium (digital technologies) arise in the development and implementation of this project.

Implementation of a methodology based on case-based reasoning, raises information management issues on a theoretical basis as well as in practical technical terms. Issues related to the overall system hierarchical structure, the choice, content and form of the example, the categorization and indexing of examples and, finally, the way to translate data between original and consequent forms. Development and applications of this tool must be in the direction of enhancing multi-disciplinarity, yet safeguarding subjectivity, in the design process. The structural hierarchy of the system, as well as the form and content of data, needs to be configured in inter-disciplinary terms, in a systematic and comprehensive way. Furthermore, the system must be flexible and allow a good deal of interaction with the designer. Therefore, the system should not impose a decision on the designer – it may only make suggestions and leave the final decision to the designer (Harty and Danaher, 1997), as opposed to preliminary design oriented tools in structural engineering that move beyond exploration of alternative solutions in selecting specific design schemes. Consequently, the software environment should focus on systematically organizing and clearly presenting the data, as well as guaranteeing easy retrieval, and not in developing complex evaluation mechanisms.

Respectively, the medium should have differentiated characteristics corresponding to the inherent nature of the design process, as well as the features of design education. The system should be able to respond to the wide range of sources, to support the structural complexity of digital files (consisting of layers, integrating a variety of presentations, referring to linked external files,...) and to incorporate the great variety of existing and new kinds of data.
(graphics, 3D models, animations, fly through, mixed presentations,…) preserving their special characteristics and avoiding homogenization. Furthermore, it should endorse qualitative approaches through visual or conceptual types of information usual in the design process. Finally, it should provide for dynamic incorporation of data, allowing for interaction with the designer.

Digital technologies have introduced a new way of organizing archive material that redefines the way information is researched, retrieved, studied and developed. The very nature of digital archives raises questions about their circulation and use; questions related to the degree of flexibility and applications of such system. Can it be open, regarding the input and modification of data, as well as the internal structural hierarchy? Is it possible to be universally applied and yet support subjectivity and individuality in design?

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References


