A Framework for Computer-Aided Conceptual Design of Building Structures

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Summary

This paper describes a framework for computer-aided conceptual design of building structures that results from building architectural considerations. The central task that is carried out during conceptual design is the synthesis of the structural system. This paper proposes a methodology for the synthesis of structural solutions. Given the nature of architectural constraints, user-model interactivity is devised as the most suitable computer methodology for driving the structural synthesis process. Taking advantage of the hierarchical organization of the structural system, this research proposes a top-down approach for structural synthesis. Through hierarchical refinement, the approach lends itself to the synthesis of global and local structural solutions. The components required for implementing the proposed methodology are briefly described. The main components have been incorporated in a proof-of-concept prototype that is being tested and validated with actual buildings.

1 Introduction

Conceptual design is the first phase of the design process where the most salient characteristics of a design artifact are defined. During conceptual building design major decisions are made regarding the building architecture, such as the internal configuration of spaces and physical elements that give shape to the building form, as well as the type and layout of the supporting engineering systems. These decisions have great impact on the constructability, cost, and overall performance of a building (Fenves et al. 2000).

A central task that takes place during conceptual design is the synthesis of design solutions into a physical whole. This task involves the exploration of potential alternatives, which are evaluated and compared based on predefined building design criteria. During conceptual design of building structures the engineer synthesizes alternative structural layouts while considering multiple conflicting building design criteria coming from the different participants involved in the design process. This research project focuses only on the impact of the architectural aspects in the structural synthesis process.

Current computer support for conceptual design of building structures is still ineffective. The main reason for this comes from the little consideration that developers and researchers have given to the architectural aspects involved at this early stage of structural design. On the one hand, the most advanced commercial efforts consider the building architecture only by allowing the selection of a few architectural elements and the construction of a 3D model without regard to functional and physical architectural concerns. On the other hand, most AI-based research efforts tend to minimize the impact of the architectural design on the structural synthesis process. As stated by Taranath (1998), until the early 1970s the structural engineer exercised considerable influence on the buildings architectural form; however, with the availability of computer techniques the structural engineer can now analyze more complex forms, thus relaxing structural constraints for architects.

Structural systems in buildings are hierarchically organized into structural volumes, subsystems, assemblies and elements joined through connections. Consequently, the main premise of this research project is that, in order to properly support conceptual design of building structures and enable timely engineering feedback to the architect, computers must allow engineers to synthesize the structural system hierarchy within a building architectural context. Based on architectural considerations, this paper proposes a decomposition of the conceptual design process of building structures and describes the computer technologies that would efficiently assist each sub-process. Since structural synthesis is the central task that is carried out during conceptual design, this paper proposes a methodology for the synthesis of structural solutions. The methodology follows a top-down refinement approach. It has been implemented in a proof-of-concept software prototype that is being validated with actual test buildings.

The paper is organized as follows: the next section elaborates on the early stages of building design, thus providing a context for the concepts that are proposed in the rest of the paper. The following section briefly describes the kind of integration that is required between the structural system and the building architecture followed by a closer description of architectural constraints. Then, a framework for computer-assisted conceptual design of building structures is introduced. Finally, a computer-based methodology for structural synthesis is proposed following the user-model interactivity approach.

2 Stages of conceptual structural design

Design is an iterative process that follows a series of synthesis, analysis and evaluation (SAE) loops until a satisfactory solution is found. During conceptual design, however, the emphasis is on the synthesis process, while analysis is greatly simplified. The goal of the conceptual stage of structural design is to find a feasible arrangement of structural elements in space that, while responding to the requirements of the building architecture, are able to transfer, safely and efficiently, the loads to the ground. The outcome of this stage is an initial description of the structural system in terms of the layout of its members with associated cross-sectional properties, connectivities and materials.

Structural layout planning is considered by most authors to be part of the synthesis process. However, for the sake of the discussion in this paper, it is treated as a separate but complementary task. Therefore, the activities that take place during conceptual design can be summarized as follows:

(1) Structural layout planning - The engineer makes initial decisions about the structural system type and material(s), and study feasible structural layouts and corresponding cross-sectional element dimensions. To carry out structural layout planning engineers rely on sketches, as well as general architectural requirements and information about the building, for example its type, location, number of stories, etc. This allows engineers to estimate and compare materials, costs and weights of feasible structural systems even before initiating the actual design.

(2) Structural synthesis - The engineer actually arranges the structural elements in space in order to respond to the specific requirements from the architectural design. Compared to the structural layout planning, during structural synthesis the array of feasible structural solutions is reduced due to actual functional loads and physical geometry and topology constraints imposed by the architect.

(3) Simplified analysis – The engineer performs simplified analysis of conceptual design alternatives using approximate analysis techniques.

Most previous research efforts have focused on the structural layout planning process and on developing simplified analysis and evaluation techniques. By contrast few research projects have tackled the actual synthesis of structural solutions within a building architectural context. This is the focus of this research project.

3 Integration between the structural system and the building architecture

A variety of structural constraints need to be considered during the synthesis process, such as: function, behavior, performance, reliability, material, cost, compatibility and constructability constraints (Luth et. al 1991). Since the structural system is a physical arrangement of elements, all the above constraints are transformed into geometry and topology constraints. The building architecture imposes additional constraints to the synthesis process. Architectural constraints can be classified either as functional (i.e. related to the use of spaces) or physical (i.e. coming from the physical building elements, such as walls). These constraints dictate the degrees of integration between the structural system and the building architecture, namely functional integration and physical integration.

Functional Integration:

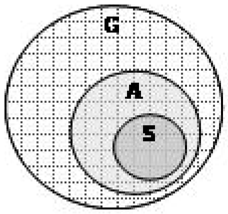
There is a natural interdependency between the overall organization of the structural system and the functional organization of spaces (Holgate 1986). In addition to the building geometry, this relation initially dictates the type of structural system and subsystems (lateral and gravity) to be used, the load patterns expected according to the occupancy and the objects in each building zone, allowable floor spans and interfaces between dissimilar building zones among others. For example, just by knowing the function of a space or a building, as well as its location, structural engineers are able to specify feasible structural systems that are likely to fulfill the functional requirements of the spaces or the entire building. Lin and Stotesbury (1988) use the term "structural zone" to describe a functional space or a group of spaces having similar structural characteristics.

Physical Integration:

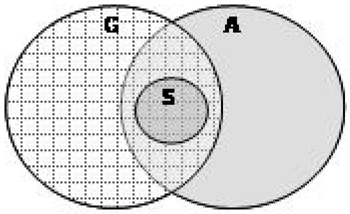
There is a strong interdependency between the layout of structural elements and the patterns defined by the architectural physical elements (Schodek 2003). An engineer's goal, in relation to the architecture, is therefore to match as closely as possible structural patterns to those defined by the architectural elements, mainly the permanent walls. By observing actual buildings and studying the patterns formed by the elements of the vertical support system and those of the building architectural elements, four levels of physical integration are identified and described using set theory as follows where:

Set G: represents the patterns formed by the project grids.
Set A: represents the patterns formed by the building architectural elements.
Set S: represents the patterns formed by the vertical structural elements.

Level 1 - This is an ideal case as it represents the best level of physical integration because the structural patterns are fully contained within the architectural patterns, so that all structural members are always "housed" by architectural elements, with no structural members lying inside spaces. In Figure 1 (a) both architectural and structural patterns perfectly adjust to a common grid. In Figure 1 (b) there are architectural elements that do not adjust to the common grid. However, these architectural elements are not structurally relevant so that the structural patterns still conveniently match the architectural patterns. Therefore, both cases represent the same level of integration.



(a)



(b)

Figure 1. Level 1 of physical integration

Level 2 - In this level, as illustrated in Figure 2, structural elements still adjust to the common grid; however, due to structural dimensional constraints the engineer must place columns inside spaces, i.e. outside the set of architectural elements.

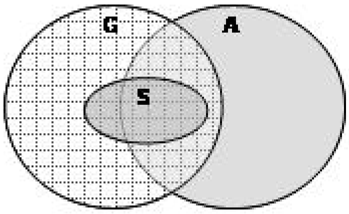


Figure 2. Level 2 of physical integration

Level 3 - In this level, some architectural elements that fall outside the common grid are structurally relevant; therefore, the engineer provides a special local framing lying outside the common grid that integrates such architectural/structural elements to the overall structural scheme (see Figure 3).

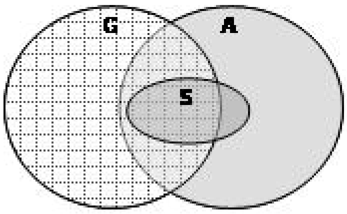


Figure 3. Level 3 of physical integration

Level 4 - This is the most general case where most structural elements match the common building grid. However on the one hand, some structural elements inevitably fall inside spaces; on the other hand, due to local architectural conditions structural elements also fall outside the common grid thus requiring a special local framing (see Figure 4).

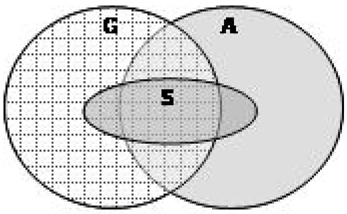


Figure 4. Level 4 of physical integration

In general, the engineer seeks to configure a structural system that matches the common grid, unless specific architectural conditions exist that demand local structural solutions. Such conditions, as described in levels 3 and 4, are the most difficult to support with computers since they usually demand specific local structural solutions. Most previous research projects, which can be classified into the structural layout planning category, provide support for the synthesis process at Levels 1 and 2, for rectangular office buildings only. This research project proposes a framework for providing computer assistance at the four levels.

4 Types of architectural physical constraints

Buildings can be categorized either as being single-cell or multiple-cell depending on the patterns generated by spaces and physical elements (Schodek 2003). For example, gyms, hockey arenas, factories and retail stores are typical single-cell buildings while apartment, office and educational buildings are multiple-cell buildings. The level of architectural constraints that is imposed to the synthesis of structural solutions depends on whether the building is single-cell or multiple-cell. Consequently, architectural physical constraints can be classified in two groups:

- ***Internal constraints*** restricting the internal geometry and topology of the structural system.
- ***External constraints*** affecting only the external shape of the structural system.

For single-cell buildings, internal constraints are minimized and sometimes eliminated. Thus, the external constraints prevail. For multiple-cell buildings, both internal and external constraints are relevant. Therefore, single-cell buildings, as well as large building zones (e.g. an indoor swimming pool or the conference room in a building) are more apt for the exploration of alternative structural schemes. By contrast, multiple-cell buildings pose great limitations for proposing alternative structural configurations. Conversely, architectural physical constraints can also present potential structural opportunities since architectural physical elements are often used as structural supports. Nevertheless, such elements impose support locations that reduce the alternatives available to the engineer.

5 A framework for computer-assisted conceptual structural design

The problem faced by engineers during conceptual design of building structures can be decomposed as illustrated in Figure 5. From architectural sketches and before having an initial architectural design, engineers can explore feasible structural alternatives during structural layout planning. The list of promising alternatives is considerably pruned when the engineer is presented with an initial architectural design. Starting with this architectural design, the engineer performs the synthesis process for the building as a whole (i.e. global synthesis). The reduced amount of internal architectural constraints simplifies the synthesis process for single-cell structures as compared to multiple-cell structures. For multiple-cell structures local structural solutions are required for large building zones (i.e. local synthesis). In both cases (i.e. for multiple-cell and single-cell structures) it is likely that a special local framing will also be required to respond to local architectural configurations that lay outside the common grid. Once a global or local structural solution has been synthesized, it can be analyzed and evaluated.

The decomposition illustrated in Figure 5 shows that a variety of computer technologies are required to support the entire conceptual structural design stage. The use of a specific computer technology depends basically on the types and stringency of architectural constraints involved. For some of the tasks indicated in Figure 5 a variety of computer techniques have already been investigated. However, the conceptual structural design process has not yet been tackled as a whole. The proposed framework aims at providing computer support for each of the sub-processes and sub-tasks that take place during conceptual structural design.

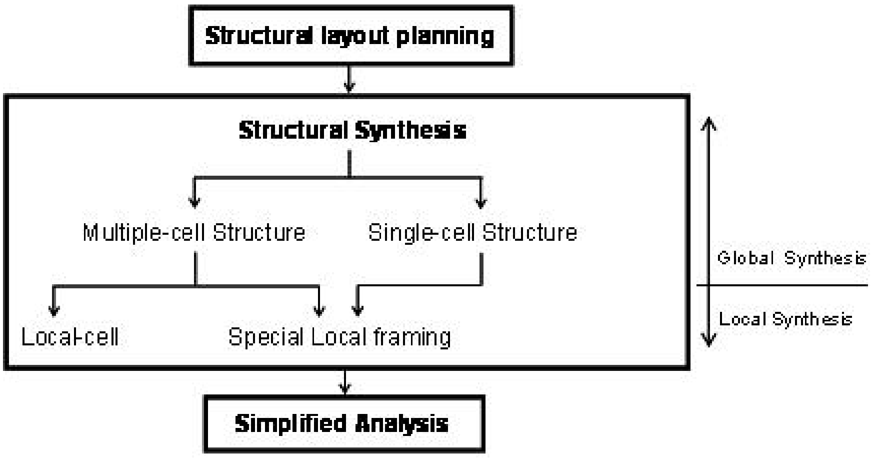


Figure 5 Decomposition of the conceptual design process for building structures

Structural layout planning – Most previous research in conceptual design of building structures can be classified in this group. Since at this point in time usually no actual architectural design exists, architectural constraints are minimized and therefore the problem can be tackled using artificial intelligence (AI) techniques. AI techniques assist engineers in exploring conceptual design alternatives and making design decisions by performing systematic search over a vast array of possible solutions under constraints. Support for structural layout planning based on AI techniques has already been extensively investigated, relevant examples are: (1) expert systems (Maher and Fenves 1985, Ravi and Bédard, 1993), (2) formal logic and engineering first principles (Jain et al. 1991, Fuyama et. al 1997), (3) grammars (Meyer 1995), (4) case-based reasoning (CBR) systems (Maher and Zhang 1993, Bailey and Smith 1994, Kumar and Raphael 1997, Rivard and Fenves 2000b), (5) fuzzy logic (Shen et al. 2001), (6) evolutionary algorithms (Grierson and Khajehpour 2002, Sisk et al. 2003, Rafiq et al. 2003) and (7) hybrid systems such as a CBR system combined with a genetic algorithm for case adaptation (Soibelman and Peña-Mora 2003).

Structural synthesis process – For simple building architectures, the results from structural layout planning can be mapped directly into the structural synthesis. However, this is not the case for most complex buildings that are erected nowadays. For complex buildings, the results from structural layout planning can be used as reference parameters for driving the structural synthesis process. For structural synthesis, the overwhelming presence of architectural functional and physical constraints precludes the use AI techniques as main mechanisms for assisting the process. Therefore, this research project proposes user-model interactivity as the most suitable mechanism for computer assistance for the synthesis process for both multiple-cell and single-cell structures. User-model interactivity allows the engineer to manipulate the model being designed while maintaining control over it as well as the tools that support its creation. These tools should also allow the engineer to inspect the building architecture and verify structural schemes. The role of geometric modeling techniques in allowing user-model interactivity is apparent since the design of any product requires reasoning in terms of geometry and topology. Commercially available structural engineering packages provide various degrees of user-model interactivity at the lowest hierarchical level only (i.e. the physical level representing structural elements and connections). Section 6 presents a methodology for enhanced user-model interactivity during the synthesis of structural solutions. The methodology is based on a top-down hierarchical refinement approach, which is intended to become the main driver for the entire structural synthesis process.

Synthesis for single-cell structures and local-cells **–** For single-cell structures and local cells (in multiple-cell structures), the reduced amount of architectural internal constraints make them suitable for using generative techniques to automatically or semi-automatically generate structural configurations. Typical applications are found in the configuration of floor, roof and truss systems. Several techniques (some of which are AI techniques) have been investigated; representative examples are the following: (1) formex algebra (Nooshin 1984), (2) shape annealing (Shea and Cagan 1998), (3) graph theory (Borkowski et al. 2002), (4) genetic algorithms (Rajeev and Krishnamoorthy 1997, Kawamura et. al 2002, Borkowski et al. 2002) and (5) sequential linear programming (Lamberti and Pappalettere 2003).

Special local framing **–** Special local framing solutions are required to respond to particular architectural design situations. For such specific design decisions it is likely that the engineer will have to interact directly with the design model locally to devise particular framing solutions. Thus, user-model interactivity is the most suitable computer technique for assisting the engineer in such particular design situations.

Simplified analysis techniques **-** Previous research projects have already investigated the use of simplified analysis techniques for conceptual structural design (e.g. Ravi and Bédard 1993, Fuyama et al. 1997). Further research is required to investigate the use of these and other techniques for analyzing conceptual structural solutions at the global and local levels.

The proposed framework is summarized as follows: structural layout planning can be adequately supported through AI techniques, as demonstrated in previous research projects. The results from structural layout planning can then be used as reference parameters for guiding the synthesis process (i.e. global synthesis). This process can then be suitably assisted through user-model interactivity following a hierarchical top-down approach. The top-down approach can be complemented with generative synthesis techniques (including AI techniques) for single-cell structures and local-cells; the suitability of such techniques has already been investigated in those design situations. Finally, the results from the synthesis stage can be analyzed globally or locally using simplified analysis techniques.

The goal of this research project is not to further investigate generative synthesis techniques or AI techniques for structural layout planning or single-cell structural synthesis. This research project pursues a broader goal which is to enable computer support for the global structural synthesis process (i.e. for a building as a whole). Global structural synthesis is the central process of conceptual structural design. Paradoxically, this is the process that has been least studied by researchers. This research project proposes user-model interactivity as the main mechanism for driving the structural synthesis process. A methodology is therefore described in section 6 for computer-aided structural synthesis. Through hierarchical refinement and problem decomposition, the methodology enables the integration of the different computer technologies that are required for assisting the engineer during the synthesis process of global and local structural solutions.

6 Methodology for synthesis based on user-model interactivity

The hierarchical organization of the structural system naturally influences the way engineers think while synthesizing structural configurations. Following this hierarchical organization, Lin and Stotesbury (1988) developed a so called "total-system" approach, which is essentially a top-down refinement approach. The total-system approach allows overall structural concepts to become contexts for thinking about local issues of detail component interactions and ensures compatibility between overall concepts and their constituent components. It also allows relating structural concepts at different levels of the structural hierarchy to architectural schemes, which enables engineering feedback to the architect at each hierarchical level.

Rivard and Fenves (2000a) proposed a design model for the conceptual design of building structures, which is inspired by the total-system approach. In this model, the structural engineer is initially concerned with establishing three-dimensional structural schemes that respond to architectural space-form schemes (Lin and Stotesbury 1988). At the structural massing level, the hierarchical representation first breaks down the structural system into independent structural volumes that are assumed to behave as structural wholes (see Figure 6). Independent structural volumes are in turn subdivided into smaller sub-volumes called structural zones. Structural zones are introduced in order to allow the definition of structural requirements that correspond to architectural functions (i.e. functional integration). Therefore, structural zones become the main mechanisms for local structural synthesis. Independent structural volumes are also decomposed into three structural subsystems, namely the foundation, the gravity, and the lateral subsystems. Each of these subsystems is further refined into structural assemblies. Finally, structural assemblies are decomposed into structural elements and their connections. Thus, through hierarchical refinements and problem decomposition, the model lends itself to the synthesis of global and local structural solutions as described in section 5 of this paper. The methodology proposed in this research project follows a total-system approach and uses the aforementioned top-down design model.

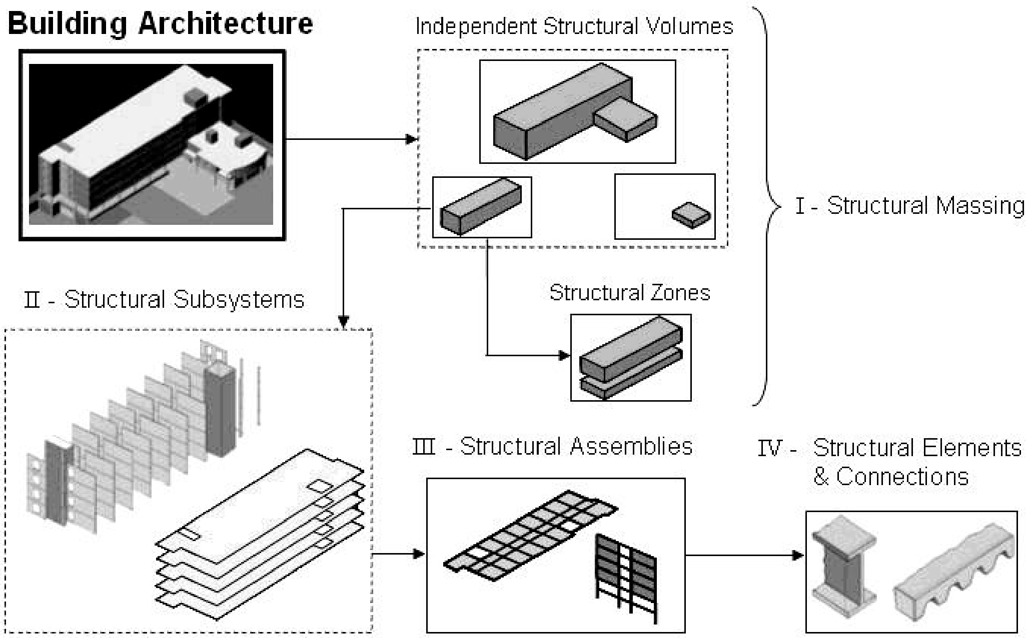


Figure 6. Top-down approach for structural synthesis

As illustrated in Figure 7, the engineer performs the synthesis process by following a sequence of steps numbered 1 to 5. In the diagram, thick vertical arrows oriented downwards indicate the top-down sequence of tasks performed by the engineer, while thin upwards arrows indicate backtracking between tasks. Activities numbered 2 and 4 have two sub-activities.

Before beginning the actual synthesis process the engineer inspects the building architecture and possibly suggests global and/or local changes to the architecture (Meyer 1995). Although this activity actually takes place throughout the entire process, it is important however to make explicit this initial engineering feedback to the architect. In activity number 1 the engineer specifies the type of structural system based on the materials, for example steel, concrete or composite structural system. Another important activity also takes place at the end of the process, which is the verification of the integrity and stability of structural systems being configured.

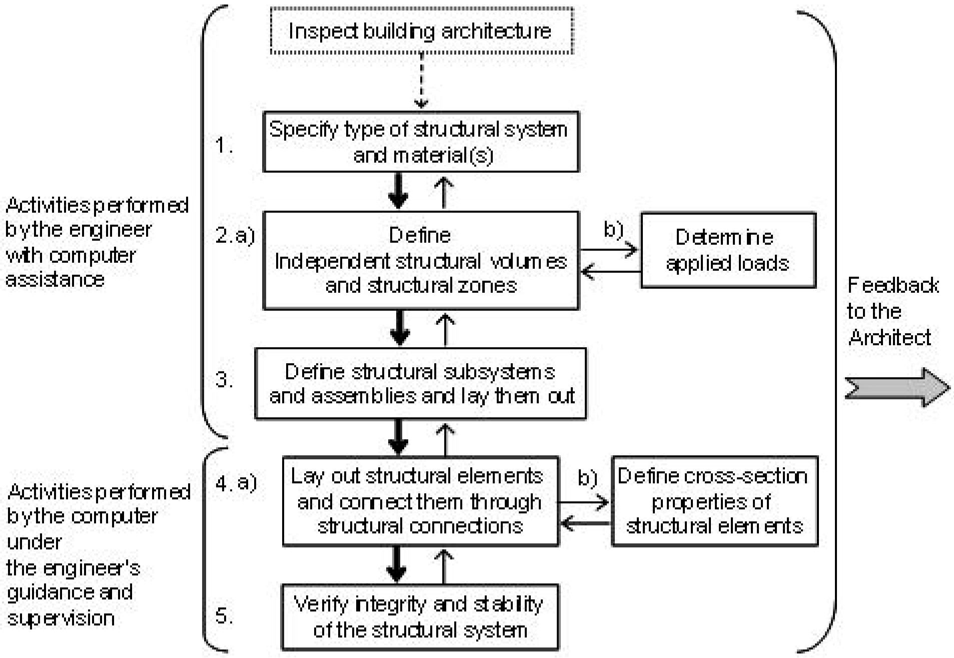


Figure 7. Design Methodology for structural synthesis (Mora et al. 2004)

As indicated in the diagram, activities numbered 1, 2 and 3 are performed by the engineer with computer assistance whereas activities numbered 4 and 5 are performed by the computer under the guidance and supervision of the engineer. Therefore, the engineer is in charge of making decisions such as selecting structural system type and material(s), as well as subsystems and assemblies, and laying them out while the computer takes care of time-consuming tasks, such as arranging and connecting elements into assemblies, under the engineer's guidance and supervision. The large horizontal arrow on the far right indicates that feedback to the architect may be provided at any step during the process. This research project aims at providing computer assistance for the building inspection, as well as activities 1 through 5, except for activities 2.b) and 4.b) that will be tackled in future stages of this research.

User-model interactivity is achieved by providing computer assistance to the engineer for the following activities: (1) the inspection and verification of the building architecture, (2) the selection of relevant architectural functional and physical entities, (3) the association of structural entities to architectural entities at different levels of the structural hierarchy, (4) the integration of the structural system to the building architecture and (5) the verification of the structural system.

The proposed methodology has been implemented in a proof-of-concept software prototype that is being tested and validated with actual buildings. The software prototype has been implemented in C++ following object-oriented principles. Four main components have been identified that are required for the implementation of the methodology. These components are briefly described in the remainder of this paper; the first three components have been incorporated in the prototype. Component number 4 is left for future stages of this research.

(1) Integrated Representation – A semantically rich representation describes the structural entities at all levels of the structural hierarchy and relevant architectural entities that are essential during conceptual structural design. Thus, at each level of hierarchical refinement, structural entities are linked with their architectural counterparts for enabling functional and physical integration. The representation is developed following object-oriented principles therefore objects incorporate methods that specify how they should be related to other objects in the design model. The representation includes two types of relationships among objects: (1) class-specific relationships (e.g. aggregation, association), and (2) domain-specific relationships (e.g. supports, attached-to, connects, etc). Spatial relationships (e.g. adjacent, overlap, etc.) are not explicitly specified in the design representation since they are computed by the underlying geometric modeling kernel (Zamanian 1992). Relevant work to in develop such kind of integrated representations is reported in Khemlani et al. (1997), as well as the Industry Foundation Classes (IFC). The main drawback of these representations is that they do not support hierarchical structural refinement nor do they consider architectural functional integration.

(2) Geometric Modeling Kernel - Provides low-level geometry and topologic data structures and algorithms for representing the geometry of the design model and providing the foundation for geometrical reasoning. In the proof-of-concept software prototype, ACIS® has been used as the underlying geometric modeling kernel. ACIS® provides open architecture for developing third-party add-ins and enables the manipulation of entities of different dimensionalities in a single data structure; this feature is paramount during conceptual design of building structures where three-dimensional spaces, two-dimensional slabs and walls, one-dimensional columns and beams and zero-dimensional connections are manipulated.

(3) Synthesis algorithms - Are built on top of the Integrated Representation and the Geometric Modeling Kernel to enable user-model interactivity. Synthesis algorithms rely on geometric modeling techniques and on knowledge encapsulated in the entities of the Integrated Representation to allow the engineer to reason based on the geometry and topology of the model being created. This feature is mostly relevant during the synthesis stage of design since it is at this stage where most decisions result from geometric and topologic concerns. For example, the algorithms assist the engineer while inspecting the building architecture in: verifying the vertical continuity of walls and columns, verifying asymmetric configurations, detecting large setbacks and cantilevers, etc. They also provide assistance in finding supports for structural elements and in verifying gravity and lateral load paths to the ground.

(4) A knowledge-based reasoning component - Is responsible for managing structural engineering knowledge including function, behavior, performance, reliability, material, cost, compatibility and constructability concerns that drive the structural synthesis process. This component is required for enabling more semantically rich communications between the engineer and the computer. Semantically rich user-model interactivity translates in more meaningful feedback to the engineer from the model being created thus allowing him/her to make more informed decisions.

The above components provide the foundation for enabling user-model interactivity during structural synthesis. Readers interested in learning the details about the first three components, as well as their implementation in a software prototype are referred to Mora et al. (2004).

7 Conclusions

This paper describes a framework for computer-aided conceptual design of building structures. The proposed framework is an initial attempt to acknowledge the influence of the building architecture in the conceptual design of building structures. The framework is based on a decomposition of the conceptual design problem that results from building architectural considerations. The framework integrates various computer techniques, each tailored towards a specific conceptual design task. This research project focuses on the structural synthesis process of the proposed framework. Given the nature of architectural constraints, user-model interactivity is proposed as the most suitable mechanism for computer assistance during the synthesis process. Taking advantage of the hierarchical organization of the structural system, this research proposes a top-down approach for structural synthesis. Through hierarchical refinement, the approach lends itself to the synthesis of global and local structural solutions. The top-down approach relies on four main components: (1) an integrated representation describing architectural and structural components that are relevant during conceptual design, (2) a geometric modeling kernel providing the low-level geometric and topologic foundations for the design, (3) synthesis algorithms that allow the engineer to interact with the model being designed and reason in terms of geometry and topology of the model, and (4) a knowledge-based reasoning framework for more semantically rich user-model interactivity. A software prototype has been implemented that incorporates the first three components. The prototype is being validated with building test cases.

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