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A geometric modelling framework for conceptual structural design from early digital architectural models

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Abstract

Computer support for conceptual structural design is still ineffective. This is due, in part, to the fact that current computer applications do not recognize that structural design and architectural design are highly interdependent processes, particularly at the early stages. The goal of this research is to assist structural engineers at the conceptual stage with early digital architectural models. This paper presents a geometric modeling framework for facilitating the engineers' interactions with architectural models in order to detect potential structural problems, uncover opportunities, respect constraints, and ultimately synthesize structural solutions interactively with architectural models. It consists of a process model, a representation model and synthesis algorithms to assist the engineer on demand at different stages of the design process. The process model follows a top-down approach for design refinements. The representation model describes the structural system as a hierarchy of entities with architectural counterparts. The algorithms rely on geometric and topologic relationships between entities in the architectural model and a partial structural model to help advance the synthesis process. A prototype system called `StAr` (Structure–Architecture) implements this framework. A case study illustrates how the framework can be used to support the conceptual structural design process.

Keywords: Geometric modeling; Conceptual structural design; Integrated design; Architectural design

1. Introduction

Computer support for conceptual structural design is still ineffective mainly because existing structural engineering applications do not recognize that structural design and architectural design are highly interdependent processes. Initially, informal engineering feedback to the architect can take place even before an architectural design is available during functional space planning. During this stage decisions are constrained by overall parameters such as building type and location, architectural preferences, etc., while considering available construction technologies and materials, constructability, and cost for decision making. Most previous research projects in support for conceptual structural design focused on assisting this planning stage (i.e. a planning problem) using artificial intelligence (AI) techniques. The problem changes radically when an architectural design is communicated to the engineer (i.e. a model-based design problem). The design can be presented in the form of sketches, blueprints, two-dimensional (2D) CAD drawings (i.e. floor plans, sections and elevations), mock-ups, or three-dimensional (3D) digital models. In the context of conceptual structural design, the availability of an architectural model for the engineer allows the following: architectural model query and interpretation, possibly architectural model modification as a result of structural feedback, and structural model generation for architecture–structure integration.

The main goal of the engineer is to devise feasible structural solutions (in terms of structural system type, material, layout, and preliminary dimensions) while respecting the building architectural patterns and constraints, and

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responding to the design intent of the owner and the architect. Thus, the emphasis during conceptual structural design is on the synthesis of structural solutions (i.e. form and function) and not on structural analysis, or determination of the behavior. During this stage the engineer makes decisions regarding the form of the structure by reasoning about its geometry and topology, while focusing on the functional requirement of load transfer. These decisions are based mostly on knowledge about the behavior and on experience about the applicability of available construction technologies and materials for a given design situation.

Knowledge acquisition studies [1], protocol studies [2] and personal interviews with engineers [3] show that when presented with an architectural design, engineers carefully inspect the design looking for load paths to the ground and potential structural problems. In doing so, engineers superimpose floor plans and check for correspondences with sections and elevations. While devising possible structural solutions, the engineer considers the functionality of the spaces to detect structural constraints and walls to verify if they can house structural elements. A 3D model of the architecture helps in the visualization of the design. However, it does not provide further insights into design intents. After some initial negotiations with the architect, the engineer either sketches structural layouts over the architectural blueprints, and let technicians input the layouts into the computer, or generates complete structural models using the CAD drawings as a reference base.

The objective of this research is to propose a geometric modeling framework to assist the engineer in providing timely engineering feedback to the architect. This is achieved by assisting the engineer with architectural models to detect potential structural problems, uncover opportunities, respect constraints, and ultimately integrate structural solutions to the architecture. User interactivity is a main requirement that originated from and was emphasized in the interviews with engineers. Interactivity means that the engineer is always in control of the process. The solution proposed in this paper is therefore neither automated reasoning nor generative design. It is an interactive, algorithmic-based approach in which the engineer requests the execution of algorithms on demand to query the model and obtain information necessary to carry out a task at hand, and to advance the design process to a new level of detail. The scope is to support the design of most typical buildings such as office, apartment and institutional buildings. "Sculptural" buildings such as the Guggenheim Museum in Bilbao are excluded.

This paper is organized as follows. The first section presents the basic requirements for an application to support conceptual structural design from architectural models. The next section presents a review of commercial packages that provide some support for conceptual structural design. The following section discusses previous pertinent research projects in structural design. The proposed geometric modeling framework for conceptual structural design is then presented; followed by an example of an interactive design session. Finally, a comparison between the implemented approach and a commercial application is presented.

2. Basic requirements for conceptual structural design from architectural models

The basic requirements for a computer application to support conceptual structural design have been identified from previous research [1–5] and are listed in Table 1. Computer support for several of these requirements already exists in commercial applications. For example Autodesk Revit Structure 3 [6] includes capabilities such as: alternative management (design exploration), changes management (design coordination and refinement), element grouping (automate repetitive tasks, constructability), and versioning (design evolution).

This work addresses all the requirements to some extent. In Table 1, the shades of grey differentiate the requirements that have been addressed in this research (dark) from those that have only been referred to indirectly (light). The latter requirements have not been tackled yet in order to narrow the scope of the research. The numbers in the left of Table 1 identify each requirement, and are referred to in Section 9.

3. Existing structural engineering software

Typical structural engineering applications include capabilities for structural system generation and modeling in a 3D context (e.g. SAP2000 [7]). Such applications are limited to a bottom-up generation (i.e. element by element) of detailed 3D models of the structure using actual structural elements (e.g. beams and columns) with cross-sectional properties selected from tables. They also enable the selection, sizing, and optimization of assemblies (e.g. frames and floors), elements, and connections using materials such as steel and reinforced concrete, as well as composite construction. Once a structural model is generated, these packages perform analysis for predicting the behavior of complex structures under several load combinations. Some of these applications (e.g. ETABS [8]) have been conceived specifically for modeling building structures. Model generation is usually storey-wise. The main drawback of the above packages is that they provide little consideration for architectural factors that influence structural designs.

More recently, some integrated applications have emerged that help the engineer to produce the 3D model of the structural system directly from the building architecture by using building information models. These rely on advanced modeling capabilities that combine and link automatically different representations of design models and parametric capabilities that facilitate model modifications. Examples are Revit Structure [6] and IdeCAD [9]. This new set of integrated applications facilitates the task of constructing structural models directly from the architecture by selecting architectural elements and integrating