INTERACTIVE KNOWLEDGE-BASED ASSISTANCE FOR CONCEPTUAL DESIGN OF BUILDING STRUCTURES

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Abstract

During conceptual structural design the engineer proposes initial structural solutions to early architectural designs. At this stage, the decisions made by the engineer are based mostly on knowledge about structural behaviours and experience on the applicability of available construction technologies and materials to different design situations. This research proposes a knowledge-based computer approach to assist the engineer in proposing feasible structural solutions to the architect interactively. With this approach a structural solution is developed by the engineer from an overall description to a specific one through the progressive use of knowledge. A first prototype has been implemented and is being enhanced with a knowledge-base for design exploration. Therefore, an example of envisioned computer support is used to illustrate the capabilities of the proposed approach.

1. Introduction

Conceptual design is explorative in nature. During conceptual structural design, the engineer devises and compares feasible structural solutions to transfer loads to the ground safely and efficiently within a building architectural context (i.e. structural synthesis). The decisions made by the engineer are based mostly on knowledge about structural behaviours and experience on the applicability of available construction technologies and materials to different design situations. Due to the limited availability of resources, knowledge and experience minimize the need for time consuming analysis for decision making at this stage. However, the trade-off between knowledge and analysis depends on the building complexity (i.e. the more complex the building, the more analysis may be required to verify and evaluate proposed conceptual structural solutions).

Nowadays, advanced computer modeling tools are available to support structural system generation, analysis, and the integration to the architecture (Khemlani K, 2005). This kind of support is model-based since it relies on the geometric and data modeling capabilities of a building information model (BIM) that combines the building architecture with other disciplines. It has been demonstrated in practice (Solibri Inc., 2005) that explicit knowledge can be used in conjunction with BIM models in the form of requirements. These requirements constrain the model and maintain its consistency when changes take place. This type of knowledge support could be called passive since it validates or confirms design decisions that have already been made. However, these tools lack the knowledge required to assist the engineer to explore design alternatives and make decisions actively.

This paper proposes a knowledge-based approach that aims at providing interactive support for decision-making to help the engineer in the exploration of design alternatives and efficient generation of structural solutions. With this approach a structural solution is developed by the engineer from an abstract description to a specific one, through the progressive application of knowledge. Thus, knowledge is used by the engineer to refine conceptual structural design descriptions interactively. The approach is applicable to most typical buildings, such as office, apartment and institutional buildings of standard shape. "Sculptural" buildings such as the Guggenheim Museum in Bilbao, Spain are thus excluded. The paper is organized as follows: the next section summarizes relevant research in assisting structural design exploration. Then, the proposed approach for interactive knowledge-based

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support is presented, followed by the components used for its implementation. Next an example illustrates the advantages of the approach. An example of envisioned computer support is used to illustrate the capabilities of the proposed approach because a working prototype for knowledge-based support is currently being implemented.

2. Literature Review

Over the last three decades researchers have applied artificial intelligence (AI) techniques to assist engineers in exploring design alternatives over a vast array of possible solutions under constraints. Relevant techniques and examples are the following: expert systems (Maher 1988, Bédard and Ravi 1991), formal logic (Jain, Krawinkler and Law 1991, Eisfeld and Scherer 2003), grammars (Meyer 1995, Shea and Cagan 1998), case-based reasoning (CBR) systems (Bailey and Smith 1994, Kumar and Raphael 1997), evolutionary algorithms (Grierson and Khajehpour 2002, Sisk, Miles and Moore 2003, Rafiq, and Mathews and Bullock 2003) and hybrid systems that combine AI techniques such as a CBR system with a genetic algorithm (Soibelman and Peña-Mora 2000).

The impact of AI-based methods in design practice is negligible mainly because many of the proposed systems are standalone with no interactions with design representations currently employed in practice, such as building information models (BIM). In fact, only three of the above research projects (Meyer 1995, Bailey and Smith 1994 and Kumar and Raphael 1997) use architectural models with 3D geometry as input for structural synthesis. In the absence of such models, global gravity and lateral load transfer solutions can be explored to satisfy overall building characteristics and requirements. However, these solutions need actual architectural models to be substantiated and validated.

Another disadvantage of the above research systems that hinders their practical use is that the support provided is mainly automatic and the reasoning supported is monotonic (i.e. based on some inputs, these systems produce outputs that meet specified requirements). By contrast, a hierarchical decomposition/refinement (i.e. top-down) approach to conceptual design is followed in this research. This approach enables knowledge-based feedback to the engineer and engineer's interactions with an architectural-structural model at various decomposition/refinement levels. A similar approach has been proposed by Sacks et al. (2000), however, their approach automates design tasks that are exclusive to architects and engineers, such as positioning spaces and proposing structural layouts. In addition, it provides no interactions with building architectural models. The approach proposed in this paper is described in the next section.

3. Interactive Knowledge-Based Support for Conceptual Structural Design

A hierarchical decomposition/refinement approach to conceptual design is adopted in this research where different abstraction levels provide the main guidance for knowledge modeling. This approach is based on a top-down process model proposed by Rivard and Fenves (2000). To implement this approach the structural system is described as a hierarchy of entities where abstract functional entities, which are defined first, facilitate the definition of their constituent ones.

Figure 1 illustrates the conceptual structural design process. In Figure 1, activities are shown in rectangles, bold arrows pointing downwards indicate a sequence between activities, arrows pointing upwards indicate backtracking, and two horizontal parallel lines linking two activities indicate that these can be carried out in parallel. For clarity, in Figure 1 courier bold 10 point typeface is used to identify structural entities. As shown in Figure 1, the structural engineer first defines independent structural volumes holding self-contained structural skeletons that are assumed to behave as structural wholes. These volumes are in turn subdivided into smaller sub-volumes called structural zones that are introduced in order to allow definition of structural requirements that correspond to architectural functions (i.e. applied loads, allowed vertical supports and floor spans). Independent structural volumes are also decomposed into three structural subsystems, namely the horizontal, the vertical gravity, and the vertical lateral subsystems (the foundation subsystem is not considered in this research project). Each of these structural subsystems is further refined into structural assemblies (e.g. frame and floor assemblies), which are made out of structural elements and structural connections. The arrangement of structural elements and structural connections makes up the "physical structural system".

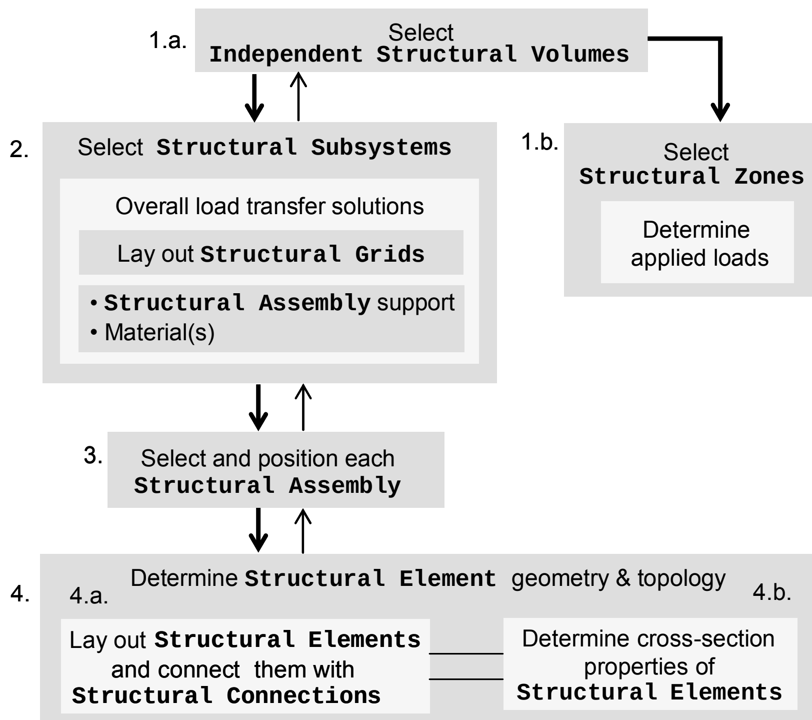


Figure 1. Simplified conceptual structural design

During activity number 2 in Figure 1 (i.e. select structural subsystems), the engineer defines overall load transfer solutions described in terms of supporting structural assemblies and corresponding material(s) and worked out based on tentative structural grids. An example of a structural solution at the subsystem level is the following: for a 9 by 12 structural grid, provide steel rigid frames for lateral support in the long building direction, steel braced frames for lateral support in the shortest direction, columns for vertical gravity support, and composite steel deck on W shape beams for horizontal gravity support. Structural grids determine tentative vertical supports (at gridline intersections), structural bays, likely floor framing directions, and floor spans.

Interactivity is intended between a structural engineer, a simplified model of the building architecture and the structural system, Architecture-Structure Model (ASM), simplified for conceptual design, and a structural design knowledge manager (DKM). During the synthesis process, an architectural model is made available first to the engineer. Then, with the progressive use of knowledge from the DKM the structural system is integrated to the architecture and the result is an integrated architecture-structure model (ASM). Table 1 summarizes the types of interactions that take place at each step of the process between the engineer, the ASM and the DKM. In Table 1 a pre-processing and a post-processing activity in the process are included (versus Figure 1). The pre-processing activity is an inspection of the architectural model, whereas the post-processing activity is the verification of the structural model.

Table 1. Interactivity table between the engineer, the ASM and the DKM

Engineer	ASM	DKM
Architectural Model Inspection		
Query – Look for potential structural problems, continuous load paths to the ground and constraints. Select - Select elements that may become structural	Display the architectural model Emphasize continuous physical elements from this model Highlight architectural grids (i.e. main functional dimensions) Display global dimensional/layout constraints	N/A
1.a. Select `Independent Structural Volumes (ISV)`		
Query - Verify building shape, occupancies, lengths and proportions. Select - Select ISV by grouping spaces.	Emphasize spaces Compute overall building dimensions and aspect ratios	Suggest seismic/expansion joints if applicable
1.b. Select `Structural Zones`		
Query - Check types of spaces and associated constraints Select - Select structural zones by grouping spaces	Emphasize spaces Show space occupancies Display space layout/dimensional constraints	Assign loads to each zone based on its occupancy
2. Select `Structural Subsystems`		
Query - Inspect the model globally Select - Select structural subsystems and materials • Structural assembly support • Material(s) • Lay out structural grids	Display overall building characteristics Display global architectural layout/dimensional constraints Emphasize architectural elements selected to become structural	Suggest structural subsystems and materials Rank overall structural solutions
3. Select and position `Structural Assemblies`		
Select - Select each structural assembly Verify – Validate the initial description from level 2 Specify - Position each assembly Lay out - May determine preferred floor framing directions	Display structural grids Display applied loads Display local architectural layout/dimensional constraints Emphasize architectural elements selected to become structural	Suggest feasible structural assemblies Rank structural assemblies
4. Determine `Structural Element` geometry and topology		
Verify- Anticipate problematic supporting conditions locally Lay out - May position special structural elements and supports locally	Emphasize openings and irregularities in assemblies Elaborate - Make selected architectural elements structural Compute element loads based on tributary areas	Elaborate - Lay out and connect primary structural elements (within gridlines) Elaborate – Lay out and connect secondary structural elements Refine – Select preliminary cross-section shape and size of structural members
Structural system verification		
Verification - Verify and support still unsupported members Verification - Verify critical members	Warn about lack of supports and show unsupported elements	N/A

As seen in Table 1 the main tasks performed by the engineer, the ASM and the DKM are the following: (1) the engineer queries the ASM model, selects entities, specifies, positions and lays out assemblies and elements, and verifies structural solutions. (2) The ASM model displays and emphasizes information accordingly, elaborates engineer's decisions, performs simple calculations on demand, and warns the engineer when supports are missing. And (3) the DKM suggests and ranks solutions, assigns loads, and elaborates and refines engineer's structural selections and layouts. Each activity performed by the engineer advances a structural solution and provides the course of action to enable the ASM and the DKM to perform subsequent tasks accordingly.

3.1. Knowledge-Based Exploration of Structural Alternatives

The knowledge-based exploration of structural alternatives takes place mostly at the abstraction levels of activities 2, 3, and 4 in Figure 1 and Table 1. At each subsequent level more information and knowledge is made available so that previously made decision can be validated and more accurate decisions can be made.

3.2 Select Structural Subsystems

At the structural subsystem level, overall structural solutions are studied by the engineer and described in terms of supporting assemblies and materials. Alternative structural grids are first proposed by the engineer respecting the architectural constraints from the ASM. These grids determine primary layouts for structural assemblies and elements and permit the subsequent validation of subsystem proposals by the engineer with the help of the computer. Then, for each structural subsystem, supporting assemblies are proposed by the engineer (with assistance from the DKM on demand). Next, the computer generates and places assemblies within the layout of the structural grids (i.e. structural frames) and from architectural floor slabs (i.e. for floor assemblies). Depending on the flexibility of the building architecture, the engineer and/or the DKM can propose alternative load transfer solutions based on the following factors: overall building characteristics (e.g. building location, seismic zone, type of building, size, number of stories, and construction area), building geometry (e.g. overall building dimensions and aspect ratios, main functional and bay dimensions) and predominant (i.e. global) architectural layout/dimensional constraints (i.e. that apply to the building as a whole). For a given structural layout, an approximate number of structural assemblies are obtained by the computer so that all feasible structural solutions can be ranked and evaluated by the DKM based on building requirements and preference factors. At this level, the engineer seeks to unify (if possible) the structural grids for the entire building. For buildings with multiple structural zones, structural subsystem descriptions can be detailed further. For example, in a building consisting of an apartment zone over an office zone over a parking zone, all the zones share the same vertical subsystems but each zone may require its own horizontal load transfer solution. Ensuring compatibility between the different assemblies selected can be achieved by the DKM using meta-knowledge heuristics. For example, a concrete rigid frame is compatible with a waffle slab.

3.3 Select and Position Structural Assemblies

Having the tentative structural bays determined at the subsystem level, at the structural assembly level (activity number 3) the engineer selects, specifies, positions, and validates each assembly with respect to local load conditions, supports and constraints given by the ASM. The DKM can also suggest feasible structural assemblies on demand. At this level, structural assemblies have not been populated yet with structural elements and connections. Structural assemblies already positioned at the subsystem level are modified, repositioned, or even removed by the engineer. Structural assemblies can also be added by the engineer or the DKM. For example, local space and/or storey factors (e.g. applied loads, availability of supports, layout constraints in spaces below) may even lead to partitioning a given floor assembly into two or more assemblies. At this level, structural assembly specifications consist of supporting element types organized by function, material, shape and size. This organization facilitates structural element grouping at the structural element level. For the typical bays, floor framing directions are specified and secondary element types, spacing and dimensions are determined. For evaluation, approximate assembly cost and weight can be obtained by the DKM for the bay dimensions given. At this level, ensuring element uniformity and compatibility within an assembly is cumbersome because of slight variations that may exist in architectural supports and constraints within and between stories (even within a single structural zone). ASM spatial verifications on adjacent bays combined with constructability knowledge from the DKM can be used to guarantee element uniformity and compatibility within a structural assembly.

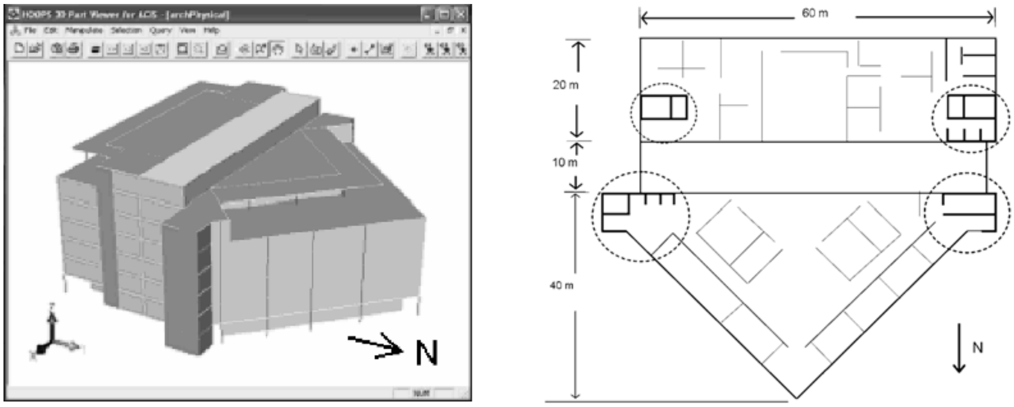
3.4 Determine Structural Element Geometry and Topology

Before structural elements are generated by the computer, the engineer verifies each assembly locally to anticipate lack of supports or critically loaded bay sections. To assist the engineer, the ASM emphasizes openings and irregularities in assemblies. Then, the engineer may place local supports that will not be generated by the computer because they fall outside the overall structural layout. Next, the DKM and the ASM generate the physical structure. The ASM verifies that all structural elements are properly supported based on the specifications from the structural assembly to which these belong. If elements not properly supported exist, the ASM warns the engineer about the lack of supports. Alternative structural element's cross-section shape and dimensions can be proposed by the DKM based on element loading and support conditions, and considering element uniformity and compatibility within the floor assemblies to which these belong.

4. Implementation of the Proposed Approach

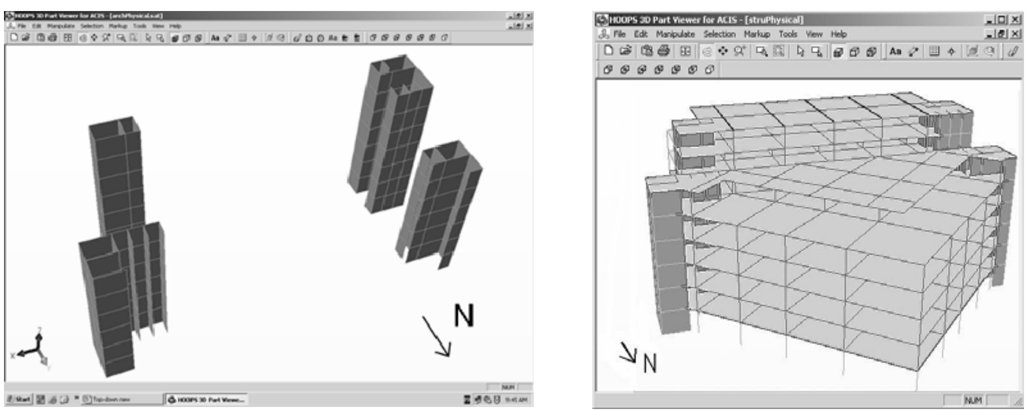
The implementation of the approach is based on an existing prototype for conceptual structural design which is called StAr (Structure-Architecture). StAr is a prototype system that assists engineers in the inspection of a 3D architectural model (e.g. while searching for continuous load paths to the ground) and the configuration of structural solutions. Assistance is based on geometrical reasoning algorithms (GRA), (Mora et al. 2006B) and an integrated architecture-structure representation model (ASM), (Mora et al. 2006A). The building architecture in the ASM representation model describes architectural entities such as stories, spaces and space aggregations, and space establishing elements such as walls, columns and slabs. Figure 2 illustrates an architectural model in StAr. The structural system is described in StAr as a hierarchy of entities to enable a top-down design approach, as discussed in section 3. Figure 3a illustrates core walls identified by StAr as continuous and selected by the engineer as structural, and Figure 3b presents the structural system generated by StAr. The geometric algorithms in StAr use the geometry and topology of the ASM model to construct new geometry and topology, and to verify the model. The algorithms are enhanced with embedded structural knowledge regarding layout and dimensional thresholds of applicability for structural assemblies made out of cast-in-place concrete. However, this knowledge is not sufficient for assisting engineers during conceptual design. StAr provides the kind of support described in the second column of Table 1, plus limited knowledge-based support (column 3) at levels 1.b and 4. Therefore, StAr is able to generate and verify a physical structure based on information obtained from precedent levels. However, no knowledge-based support is provided by StAr for exploration at levels 2, 3 and 4. This is the subject of this research. In addition, work is currently in progress to provide StAr with a graphical user interface (GUI) for inputs to replace the current interface with alphanumeric interactions with graphical outputs.

A structural design knowledge manager (DKM) is therefore being developed that gets architectural and/or partial structural information from the ASM directly or via GRA to assist the engineer to conceive, elaborate and refine structural solutions interactively. Once the engineer accepts a solution suggested by the DKM, it automatically updates (i.e. elaborates or refines) the partial ASM. Architectural requirements in the form of model constraints (e.g. floor depths, column-free spaces, etc.) from the ASM model are also considered by the DKM for decision-making.



(a) 3D view of the architectural model (b) typical floor plan

Figure 2. Architectural model in StAr (after Mora et al. 2006B)



(a) Structural walls selected by the engineer using StAr (b) Structural system generated by StAr

Figure 3. Structural system in StAr (after Mora et al. 2006B)

The DKM encapsulates structural design knowledge by means of a set of technology nodes (Gomez 1998, and Fenves S.J., Rivard H., and Gomez N. 2000). The type of knowledge incorporated in the nodes is heuristic and considers available materials, construction technologies, constructability, cost and weight. A technology node represents the knowledge required to implement one design step (in the top-down hierarchy) utilizing a specific construction system or component. Nodes are organized into a hierarchy ranging from nodes dealing with abstract concepts (e.g. a structural subsystem) to those dealing with specific building entities (e.g. a reinforced concrete beam). The application of a technology node to a building entity from the ASM can be interpreted as making one decision about a design solution. Technology nodes support non-monotonic reasoning since they let the engineer retract any decision node and select another path in the technology tree.

Given that the StAr prototype is being enhanced with the design knowledge manager (DKM), the example that follows illustrates the envisioned support for interactive exploration of conceptual structural design solutions. In the example, the support already provided by StAr is indicated as well as the support envisioned by the DKM. DKM-StAr is used to indicate that some basic support is already provided by StAr but enhanced support is required from the DKM.

5. Example of Knowledge-Based Interactive Support for Conceptual Structural Design

As explained in section 1, the approach is applicable to most typical buildings, such as office, apartment and institutional buildings of standard (i.e. non-sculptural) shape. However, the example uses a deceptively simple office building with little architectural constraints in order to emphasize the knowledge-based interactive exploration of structural alternatives. Office buildings are characterized by having flexible space layouts which provides more room for structural layout exploration at the subsystem level. The building has a rectangular shape with 12-stories of offices, two parking levels underground. The building is located in an intermediate seismic zone. As shown in Figure 4 the building dimensions in plan are 48 m x 18 m. A 12 m x 6 m vertical circulation core is located at the center of the building. Column-free stories are preferred by the architect, storey heights are limited, and the façade must be as free as possible from structural elements. In Figure 4, space-organizing architectural grids are laid out and tentative column locations are proposed by the architect. However, the functional dimensions from the architecture are multiples of 3 m (e.g. 6 m, 9 m, 12 m, 18 m, etc). These dimensions are suitable to accommodate the parking spaces underground.

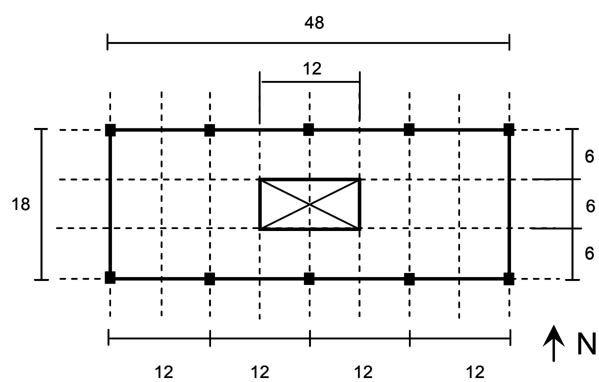


Figure 4. Floor plan of example office building (dimensions in meters)

After the inspection of the architectural model, the engineer selects the core walls to become structural. Then engineer defines one independent structural volume for the entire building. For this example no seismic or expansion joints are necessary as confirmed by the DKM. Next, the engineer selects four structural zones and the computer assigns applied loads to them accordingly: one for the parking stories (2.4 kN/m^2), a second zone grouping all the spaces in the ground floor (4.8 kN/m^2), a third zone grouping the office levels above the ground (2.4 kN/m^2), and a fourth zone being the equipment penthouse on top (3.6 kN/m^2). The current implementation of StAr assists the engineer in performing these initial tasks.

Next, the engineer explores overall load-transfer solutions (structural subsystems) as follows: vertical gravity loads will be transmitted primarily through column stacks and partly through the central core. Horizontal and lateral load transmission can be accomplished in several ways. For lateral loads the load transfer alternatives can be summarized: (1) rigid frames in one or both directions, (2) braced frames in one or both directions, (3) the central core only acting as a tube, (4) the building perimeter and the core acting as concentric tubes, and (5) a combination of the above. Through simple calculations the engineer verifies that the central core alone does not provide sufficient rigidity for overturning. Therefore, alternative number (3) is eliminated. Alternative number (4) is also eliminated because it involves overcrowding the façade with structural elements. In order to select an overall load transfer solution for the building, the engineer decides to explore three alternative structural layouts that s/he sketches using StAr (see Figure 5).

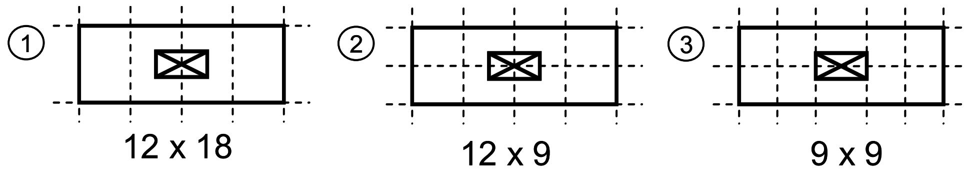


Figure 5. Alternative structural grids

For each structural layout the engineer proposes suitable load transfer solutions (using his/her own experience), which are validated by the DKM. Alternatively, the engineer may ask the DKM to suggest a feasible structural solution for each layout proposed. The overall load transfer solutions proposed by the engineer and validated by the DKM are described in Table 2. In Table 2, WF means wide flange (i.e. W shape beam). For all cases the engineer specifies that the building core also contributes to lateral support, and that vertical gravity load transfer is provided by column and wall stacks.

Table 2. Overall load transfer alternatives (i.e. at the subsystem level)

	# 1: 12 x 18	**# 2: 12 x 9**	**# 3: 9 x 9**
Material	steel	steel	concrete
Lateral support	braced frames	braced frames	rigid frames
Horizontal support	steel deck/open web	steel deck/open web/WF	two-way flat slab
Floor depth (mm)	1000	550	300

For the evaluation of the most suitable structural solution at the subsystem level, each solution should be ranked by the DKM considering several factors including estimated structural system cost and weight and the effect of the structure on the architectural cost, cost of the foundation, soil conditions, constructability, architectural requirements and constraints, and integration with mechanical electrical and plumbing (MEP) systems.

From a structural standpoint, alternatives number 2 and 3 are more stable because they provide more vertical supports for transferring the loads to the ground. However, these are also heavier structural solutions, alternative number 3 being the heaviest one. Alternatives number 2 and 3 are also more intrusive in spaces and facades than alternative one. However, they provide lower floor depths which are beneficial for building cost, constructability, and integration with MEP systems. Nevertheless, open web joists allow the passage of ducts and pipes through the joists. Alternatives number 2 and 3 distribute the load more uniformly over the foundation. However, heavier loads are also transmitted. The evaluation criteria can be customized to associate a weight for each factor and augmented to incorporate experiences from new projects.

With the rankings and data provided by the DKM, the engineer may try to persuade the architect to trade-off two columns inside spaces for lower building costs with shallower floor depths. It is assumed that the alternative number 2 is accepted by the architect with the condition that no braced frames should be placed. A modified alternative 2 is therefore selected with rigid frames instead of braced frames.

Then, the engineer proceeds to select and position each structural assembly individually. The DKM advises the engineer about the convenience of minimizing rigid connections with steel. For the vertical lateral subsystem, in the short direction the engineer specifies two interior rigid frames and in the long direction two rigid frames along the facades covering only the two mid-spans (see Figure 6). The remaining frames or frame sections are simple gravity. For the horizontal subsystem, a partial decision tree is described in Figure 7.

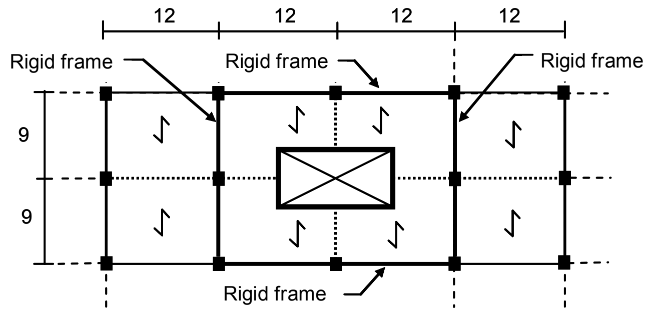


Figure 6. Floor assembly for alternative # 2 (dimensions in meters)

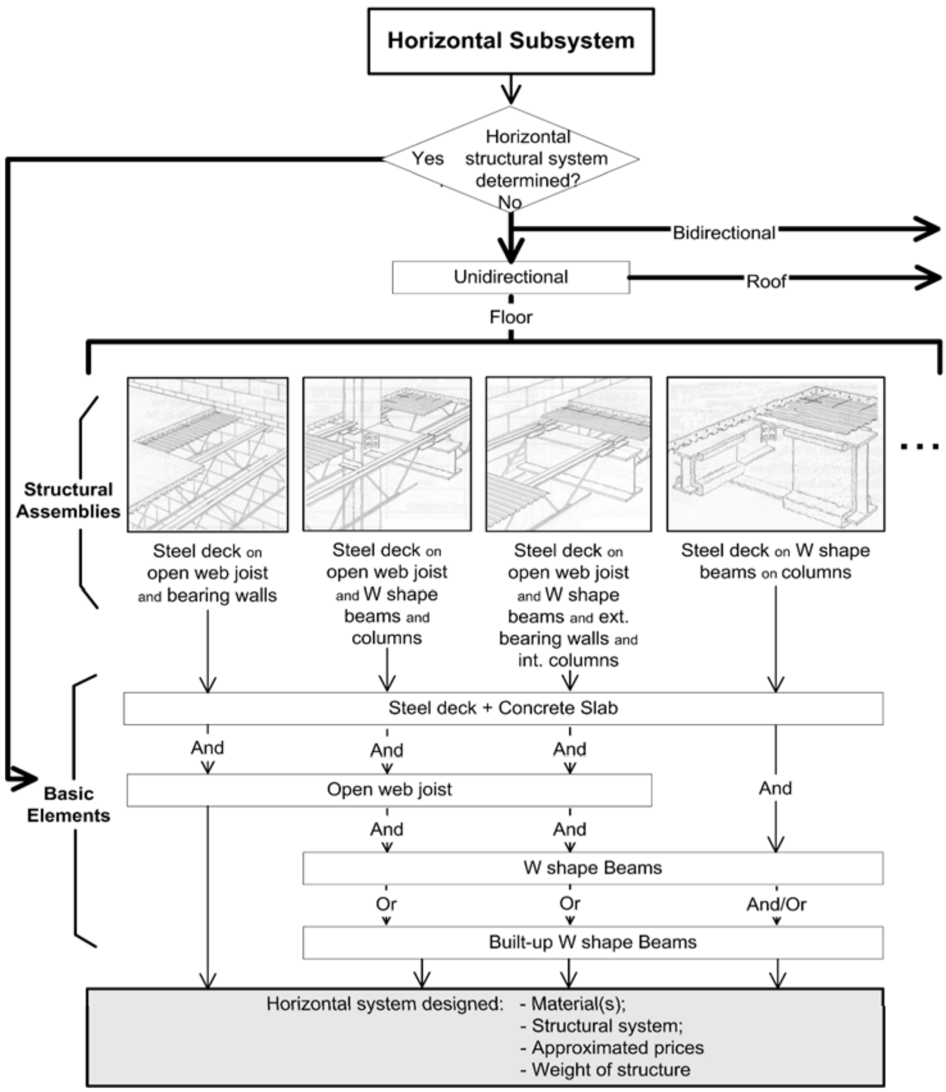


Figure 7. Partial decision tree for the horizontal subsystem (alternative # 2)

At the assembly level, the floor framing directions are determined by DKM-StAr (see Figure 6) and steel deck sections are identified, along with open web joist and W shape beam types. These are grouped by lengths (from the different bays) and the load that they carry. However, assemblies are yet populated with elements. At the element level, the engineer does not detect any openings or irregularities that may cause structural support problems and therefore no support verifications are required. Then, each floor assembly is populated with structural elements by DKM-StAr. Figure 8 illustrates a floor assembly for a typical floor (i.e. excluding the ground floor, the roof, and the first basement).

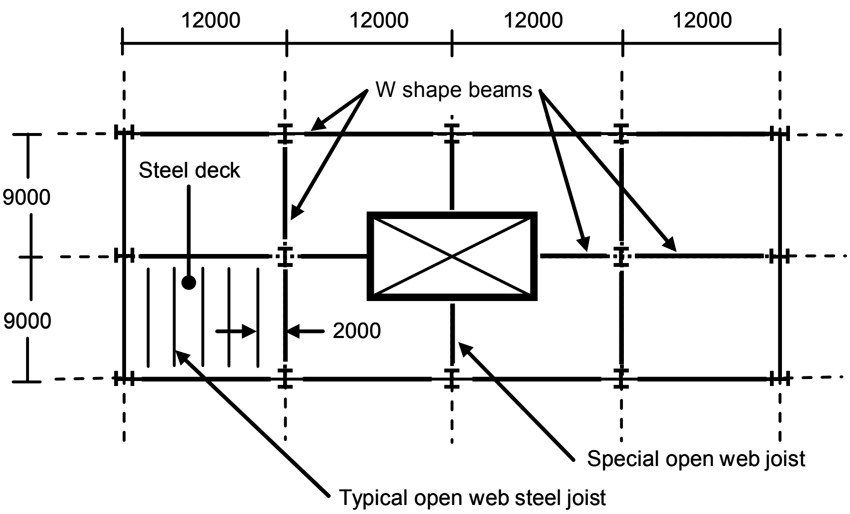


Figure 8. Floor assembly specified at the element level, alternative # 2 (dimensions in mm)

A fundamental difference between this approach and the ones proposed in section 2 is that here the architectural model is created by an architect and not by an architecturally constrained AI system, and alternative structural subsystems and layouts are proposed by the engineer and not by the computer. The computer only evaluates alternatives and suggests solutions on demand. Following this approach, the engineer can develop a structural a solution down to the assembly and element levels with knowledge-based assistance that corresponds to the level of detail required by the engineer.

6. Conclusions

An approach for knowledge-based interactive conceptual structural design has been proposed. The approach simplifies the conceptual design process by enabling the engineer to focus on the essential features only at each abstraction level while enabling quick structural synthesis. It has the following advantages over commercial applications for structural model generation: (1) it facilitates design exploration by proposing feasible design alternatives and enabling non-monotonic reasoning, (2) it constitutes a more efficient method for conceptual structural design because it simplifies the design problem by decomposition/refinement, (3) it enables more integrated design solutions because it uses structural design knowledge to evolve an architecturally constrained building information model, and (4) it facilitates decision-making and early architect-engineer negotiations by providing quantitative evaluation results. This research is work in progress. A knowledge-base is under development will be integrated to an improved StAr prototype.

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