Exploration of Interrelationships between Digital Design and Production Processes of Free-Form Complex Surfaces in a Web-Based Database

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Abstract: The intention of this paper is to examine the mutual influences of initial architectural, structural and digital manufacturing related decisions on the evolution of free-form structures. A survey on current applications will be presented to lay the foundation for the examination of new production techniques and structural concerns for the computer generated expressive forms. Finally, the paper will describe an interactive web-based database project which aims to establish a grammar on the mutual influences of architectural, structural and production related features of free-forms. Based on the built examples of blob structures, the database serves as a catalogue of possibilities related to form, and facilitate assessment of the impact of the early choices on the free-form building design and development.

1 INTRODUCTION

The dominant formal vocabulary of blobs is their complex, double-curved surfaces which have special properties from a spatial, structural and aesthetic point of view. In order to exploit this potential in a building, the design surface must be developed into rational cladding components combined with an appropriate supporting structure. Although there are built examples of complex free-form buildings (also known as *Blobs*) in which the main structural system is almost totally independent of the surface geometry, the real challenge in the current architectural and structural engineering practice is to develop the suitable structure for the architectural statement where the structural form becomes an elemental component of the architectural surface itself.

Advances in both architectural and engineering design practice, and the emerging digital manufacturing technologies have mutual influences in the development of the formal vocabulary of *Blobs* and the production of their components (Klinger 2001). In current practice, however, there is no established principle or theory concerning the design and production of free-form buildings that can be a useful source providing feedback to the designer especially in the conceptual design phase. In a CAAD environment, complex geometric forms exist entirely as surfaces without structural considerations. Parameters for gravity, material properties and manufacturing techniques can not yet be tested in design visualization software (Klinger 2001). Moreover, 3D data exchange between CAAD/CAM/CAE applications has not yet become a standard process. Therefore, to fully make use of new digital options in working with free forms, and of translating free-form structures into reality, architects and engineers must integrate their form generation and conceptual design processes with direct reference to advanced manufacturing technologies.

This paper attempts to provide a basic theory on the mutual influences and formal consequences of architectural and structural form development decisions in the conceptual design phase. Integrated process, in this paper, refers to linking the form generation processes for both architectural and structural purposes by explaining how each initial decision affects the evolution of a form and informs the choice of the production technique of its parts and components. A particular emphasis is placed on the relationship between two primary building systems for blobs; the superstructure, and the exterior and interior skin(s). In the second section, formal and tectonic implications of three exemplary structural approaches in relation to the architectural statement are examined as part of an integrated design approach. This is followed by a discussion of the role of digital manufacturing approaches in design conception and development as a part of this integration.

Finally, the paper describes an interactive web-based database project which is currently being developed as a part of three separate PhD research projects. The project attempts to establish the relationship between architectural form, structure and production of these structures and their components. Based on the hypothesis that a logical grammar which rules these relationships exists, this grammar, once established, can be used as a predictive design tool. In order to do this, an interactive database of noteworthy examples of built blob structures is being developed. This computer-based database system is to be used by architects, engineers, students and other designers, providing an interactive tool during the conceptual design stage of free form surface structures. This allows design solutions to be created interactively, promotes valid decision making (e.g. concerning structural system choice) and facilitates assessing the impact of these choices on the building design and development. It provides a case study database resource for rapid information access to possibilities related to form, structure, and production of structural parts and components.

2 CONCEPTUAL INTEGRATION OF CAAD/CAM/CAE

2.1 Mutual Influences of Skin and Structure on Free Form Surfaces

The following analysis displays how the evolution of a form is influenced by three different structural approaches in the conceptual design phase. These approaches effect, inform and transform the spatial and tectonic appearance of the architectural form and influence the production technology in a number of ways (Kloft 2001). The designers will be aware of the formal, structural and production related consequences of the initial choices by integrating these aspects into their conceptual design phase. It is also important to note that these approaches are not always intentional and may arise due to practical reasons, economic/time constraints, lack of available materials and/or production techniques which can vary for each project and play a more dominant role in the final design.

In the first approach, the form of the structural elements derives from the variations of the wire frame divisions of the digital form and follow the contours of the master 3D geometry. The master geometry is translated into rib-like structures of bones and skins and transferred into a new drawing file for engineering and manufacturing applications. The ribs are constructed as main structural frames which follow the local coordinates of the form in three directions. The resulting morphology is non directional, homogeneous where tectonic expression is more on the skin. The inconsistencies in the structure mostly occur at the acute corners where there are rapid changes in the form. Individual elements in the structure may be composed of either linear or curvilinear elements (Figure 1).

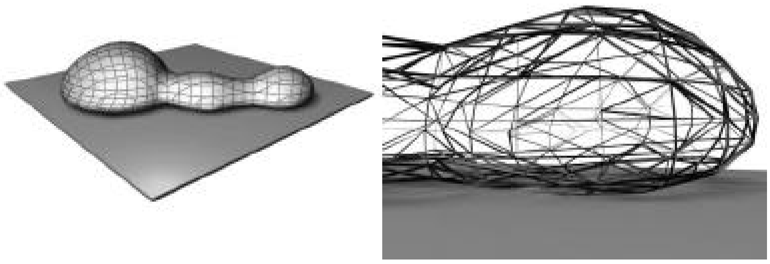

Figure 1 First Approach in Structural Form Development. Image courtesy of Gijs Joosen (Joosen 2003)

In the second approach, the structural frames are obtained either by cutting the 3D form in vertical and horizontal slices where each cross-section defines the contour of the frames or by allowing the frames to follow any two main coordinates of the master geometry. Structural elements are generally arrayed in two main directions at certain intervals. The resulting morphology is directional, composed of arch-like frames in the dominant direction and the tectonic impression is the structure itself, the form of which derives from the actual form of the skin. The actual curvilinear shape of the acute corners can only be provided by using secondary frames in a different configuration (Figure 2). When permitted, the structural form may be optimized, otherwise the frames will follow the exact geometry of the master form.

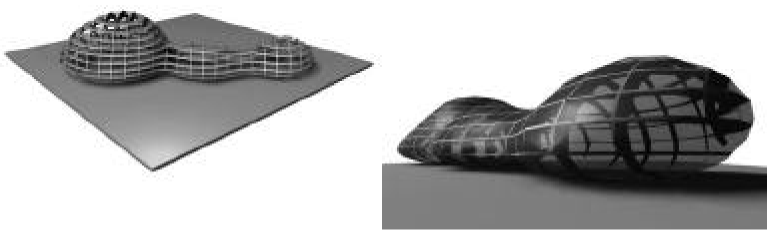

Figure 2 Second Approach in Structural Form Development. Image courtesy of Gijs Joosen (Joosen 2003)

In the third approach, the structural framework creates a wire-mesh composed of either linear or curvilinear elements (Figure 3). It is not the exact digital geometry which masters the frame composition, on the contrary, the digital form is divided into irregular surfaces which are defined and framed by the structural elements. The master geometry and the structural form are reconciled for the creation of the final surface form.

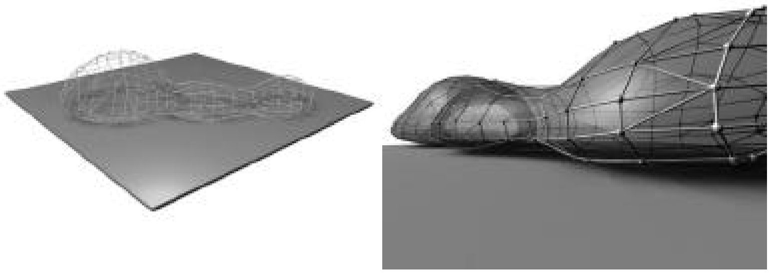

Figure 3 Third Approach in Structural Form Development. Image courtesy of Gijs Joosen (Joosen 2003)

The resulting morphology is homogeneous, non-directional and since the form is defined by both the structural elements and the surface in between, the resulting tectonic expression consists of a combination of both. In the web-based database system, which will be in section three, it will be possible for the users to visualize the formal consequences of each initial of structural design approach for various projects.

2.2 Influence of CAM Processes on Architectural and Structural Form Development

Manufacturing and production processes of components for a building could also inform the design conception and development of blob forms. "While it is increasingly common in other industries to use additive technologies to make investment castings, it is the emerging potential of processes that directly manufacture metal components from CAD models that could revolutionize the manufacturing of custom, project-specific metal architectural components" in building practice (Rotheroe 2001). Today, both 3D printing and selective laser sintering (SLS) create steel skeletal structures that are sixty percent dense. Alternatively, laser and metal powder based processes produce metal by deposition of molten metal on a layer-by-layer basis. Consequently, resultant material strengths equal or more often exceed those generated by established rolling and extrusion techniques. In aerospace industry, new methods are being developed to directly manufacture large free-form metal components which have enormous potentials to be imported to support the production of structural components in building practice. Consequently, these technologies will have a direct impact on the generation process of the architectural/structural free-forms in relation to their fabrication (Rotheroe 2001). Thus, a clear classification of fabrication processes in direct relationship with digital form-making potentials would provide a necessary outline for the development of new principles in the realization of expressive form into physical architecture. In our web-based database system, an option will be provided for the user to retrieve data on current and possible future applications of the new digital production technologies.

2.3 Building up a Theory of An Integrated Process

Recent analyses of completed building projects have revealed the fact the interrelations and mutual influences of various decisions on the form-conception depend on various constraints and variables in varying contexts. Consequently, defining and classifying these contexts, emerging relations between various processes, constraints, variables and possibilities can be a means to build up a theory of an integrated design process for free-form architectures. In the next section, we will introduce a database project as a model for the conceptual integration of design and production processes for double curved surface structures. The theoretical framework is established within a trans-disciplinary approach and particular interest is placed on the relationship between two building systems in an integrated form development process: the primary structure and the envelope surface(s). For the purpose of this study, the integrated process refers to linking the architectural approaches for exterior and interior envelopes of free-form buildings to the structural-form generation for their supporting structure in relation to digital manufacturing technologies. The database project aims to build a theory that will account for how initial formal, structural and manufacturing related decisions mutually influence, effect and inform the evolution of new configurational possibilities between the structure and the skin(s). The hypothesis is that there is a context dependent logical grammar which rules these relationships in free-form building design and production, which once established can be used as a predictive and generative tool in the form development process.

3 INTERACTIVE WEB-BASED DATABASE SYSTEM FOR CONCEPTUAL DEVELOPMENT OF FREE-FORMS

3.1 Project Description

The description and definition of the emerging relations between evolving digital architectural, structural and manufacturing potentials is essential for the development of any conceptual or computational integration of processes. This web based environment is mainly being designed as a search engine for retrieving information on design precedents in order to examine problems that traditional methods pose and the emerging potentials digital technologies offer for double-curved buildings. Hence, with the help of this database we try to establish a grammar of influences between formal, structural and production related aspects of form conception in varying contexts. Additionally, by defining these contexts we aim to describe the constraints and variables of these influences for each context.

First, a data structure has been developed by formulating various context independent factors (features) that are influential in the form development process. Once these features are interrelated, the case studies are entered in the digital media with reference to these interrelated features (Figure 4). Consequently, the database is designed to be used for extensive cross-referencing and interactive searches concerning which factors influence others and how these have been influential in form development in varying contexts among the constructed blob examples.

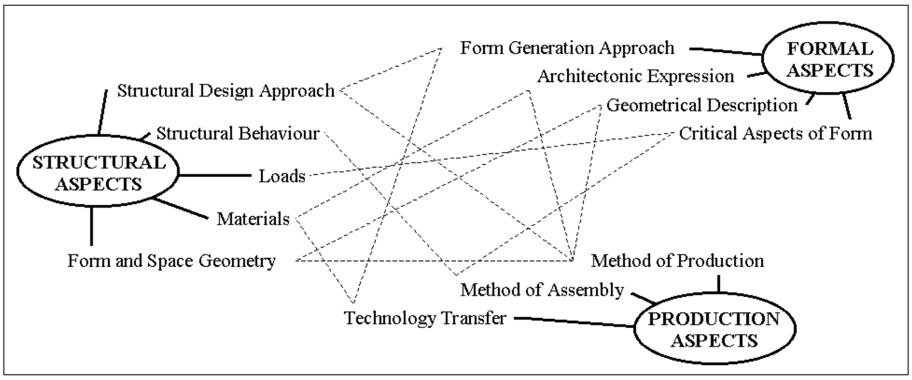

Figure 4 The Interrelated Features of Three Aspects in Free-Form Design (The relationships in the figure are indicative rather than final)

The project is still under development and initially aimed to be used in an educational context. Currently, the students are entering the results of their analysis of selected precedents in the database. It is anticipated that, once established, the database will address to architects, engineers, students and other designers as a case study database resource for rapid information access, a catalogue of possibilities related to form, structure, and production which can be used as an interactive design tool. Designers may use this search database by starting from a specific feature of their architectural form to get information to see the structural and production related consequences on their form and may visualize alternative applications in precedent projects. Or, structural engineers may start their search on "structural typology" to retrieve information on production technologies and form development processes associated with this specific typology.

3.1.1 Data Entry

Integrating various contributions (new project entry) necessitates the specification of relationships between documents across all contributions. Relating documents is best supported by providing a separate semantic structure for categorizing these documents. In such a case, authors only need to be concerned with associating the documents of their contribution to this semantic structure, relationships to documents from other contributions are automatically provided through these associations. As this relational structure becomes denser, it will offer better support for searching and browsing the information space, unrestricted by the original boundaries of the contributions (or projects). Therefore, we aim to support the authors with ways for increasing the structure's cardinality and its interrelatedness towards a richer information structure: augmenting the structure's relatedness with content information (Tuncer, Stouffs and Sariyildiz 2001).

Instead of a list of categories or keywords, we introduce a keyword network, which provides an outline for organizing and categorizing information. Such a keyword network provides the authors with a structure to categorize their contributions. The keyword network defines the context for the organization of documents. The distinction between semantic (keyword network) and syntactic (document structure) structures ensures extensibility and flexibility of the overall representation, because the semantics can easily be altered at any time without requiring an adaptation of the syntactic structure. As such it avoids the imposition of a fixed frame of reference.

3.1.2 Representation

The content to the system is provided as a number of documents from selected precedents (projects) and a keyword (aspects/features) network. The keyword network depicts the semantic structure for this document structure, with each document entity assigned one keyword from the keyword network. The keyword network is predefined and serves as an access point into the system. Both keyword and document structures are recursively defined.

In this organization of keywords and documents, various kinds of document relationships can be distinguished. Documents are grouped under projects. By assigning keywords to documents, documents that share the same keyword are implicitly related. The keyword network further relates documents; these relationships are derived from the nesting of the respective keywords.

3.1.3 User Interface

Since the aim of the database is to allow cross-referencing between multiple projects, the user interface is optimised on this aspect. At any time, the screen layout provides feedback to the user about which aspect or feature he is exploring and to which projects they are associated. This allows both browsing to a more specific feature – so called forward browsing – as well as for a more general feature – referred to as backward-browsing.

Currently, the main starting point for data-retrieval is the predefined keyword network structure, in frame A, on the left hand side of the screen (Figure 5, A). The selected feature(s) will be highlighted and displayed in the frame B on the top right hand side with the other features associated with it (Figure 5, B). These associated features are predefined within the keyword network structure. For example selecting *Structural Behaviour* feature under the *Structural Aspects* will be associated with features such as; *Material* under the *Structural Aspects, Geometrical Description* under the *Formal Aspects* and *Production Method* under the *Production Aspects*. By the use of a slider, the user can choose the degree of sub-features to be displayed in this window. Specific project-related content is stored in documents, which are related to the predefined features.

Clicking on a feature in window A or B will display the related project documents in frame C which contain textual, graphical or numerical data containing information on the selected feature and its associated features (Figure 5, C). If one of the documents is selected in frame C, frame D will then display specific information on the selected project and will name all the features associated with this project (Figure 5, D). Selecting a feature in frame A will display general and project independent information on the selected feature in frame D (Figure 6).

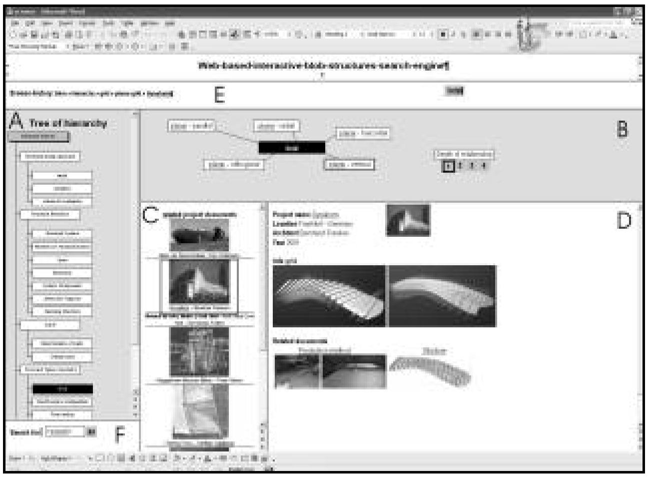

Figure 5 A Screen-shot of the interface; Frames: A) aspects and features , B) relationships , C) project documents, D) content, E) browse history, F) search

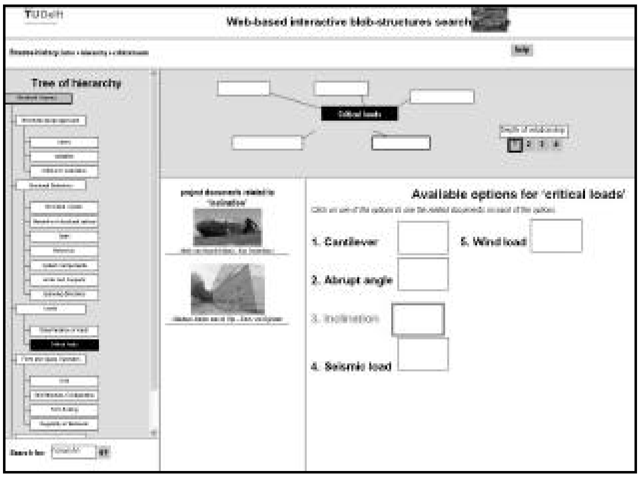

Figure 6 Screen-shot of the interface: Frame D will initially display general information on the selected feature

3.2 Project Contribution and Future Work

There mainly two fundamental advantages of the database compared to its precedents. First, it is not only the features which are searchable but the links between two or more features can also be searched by the user to access more specific information on the relationships between specified features. Thus, the links between the features are also designed to store documents and project specific information. Second, once the data structure, searchable features and frameworks of relations among features are set, the users will be allowed to add information in the database. Thus, the database will automatically be updated with new information by user feedback (e.g., architects, manufacturers, structural engineers) and serve as an interactive medium to discover new relations among existing and new features.

Currently, we are limited by the analyses of completed building projects. As a next step, in order to use the database as a tool to explore formal potentials, existing and emerging free-form metal fabrication processes both used in the building industry and developed in other industries must be identified and added as a searchable option in the database as project independent data. This is essential for the development of a more sound theory on the emerging relationships between digital processes and their emerging influences on the form conception.

4 CONCLUSION AND DISCUSSION

At present, the formal variety and architectonic multiplicity of the new digital architectures are still an exception rather than a rule and formal experimentation cannot by itself lead to a new architecture unless its full performance is fully discovered (Ruby 2001). In fact, advances in both architectural and engineering design practice and the emerging digital manufacturing technologies have mutual influences in the development of the formal vocabulary of *Blobs*. However, in current practice, there is no established principle or theory concerning the design and production of free-form buildings which can be a useful source providing feedback to the designer especially in the conceptual form development process. This paper attempts to provide a basic theory on the formal influences of structural and manufacturing aspects on blob buildings. The web-based database, as described in the paper, attempts to integrate architectural, structural and production related features in a database of built examples of blobs, which can be used to make valid decisions during conceptual form development process of free form surfaces.

The web-based database project establishes new, explicit and systematic links between blob forms, their compositional principles and their structural and material determinants. It is anticipated that this will allow architects, structural engineers, professionals as well as architectural students to explore and evaluate the consequences of their form making decisions in relation to these influences. This interactive database may also provide the guidelines for the development of a new architectural CAAD tool which will be based on performance-based (structural and constructional) generation of free-form surfaces.

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