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CONSIDERATION OF MATERIAL BEHAVIOUR IN THE CREATIVE DESIGN PROCESS: A PERSPECTIVE FROM STRUCTURAL ENGINEERING

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Abstract: The purpose of this paper is to examine how material choices are made in practice by structural engineers and by implication how material behaviour is understood. The research uses documents from recently completed design projects. By extracting specific design ideas and decisions from project documentation and categorizing them based on the type of material knowledge, (either theoretical or technological), and the process by which the decision was made, (either intuitively or using a specific design tool to verify), the authors wish to illustrate the role of material in the creative design process undertaken by structural engineers. The results reveal a complex interconnection between material represented as matter (as defined in the theories of structures and strength of materials), and the particular nature of individual materials as understood through technological knowledge.

Keywords: *material behaviour, creative design process, technology*

1. Introduction

In the profession of structural engineering, designers are confronted with a wide range of materials, ranging in behaviour from highly variable natural materials such as soil and rock to refined metal alloys. As a result, an understanding of the breadth of possible material behaviour is fundamental to the profession's knowledge base and the designer's creative process.

1. 1 Knowledge framework: theory v technological knowledge

The theoretical basis of contemporary structural engineering was largely established with the formulation of elastic theory in the nineteenth century, (Heyman, 1998). A key concept developed in elastic theory, was the intrinsic material property which is independent of the form or geometric extent of the material. (Examples include among others Young's Modulus E and the Poisson's ratio ν). This conceptual leap was the key to the development of methods to quantify structural behaviour, but

equally, from the standpoint of material science, can be seen as a convenient approximation used to allow the development of mechanics, which contradicts the observed reality that form and material behaviour are difficult to separate. (Gordon, 1988).

In parallel to the extensive theory available to the structural engineer, (calibrated against a mass of laboratory tests on material), empirical rules of thumb and direct experience regarding material behaviour continue to form a significant portion of the structural engineer's knowledge base. Particularly with regard to materials with highly non-linear properties, such as reinforced concrete and timber, a wealth of observations of built work, provide data about movements, tears, cracks and instabilities. This information comes from a limited number of full-scale laboratory experiments, and mostly from both, the practicing engineer's active involvement in construction, and from fields such as the renovation and conservation of buildings. Critically, it can be argued that the study of full scale precedent, remains a key tool in structural engineering design education (HarvardGSD, 2010). In this paper, the authors will refer to this type of knowledge as technology based knowledge in contrast to theoretical knowledge. For a wider discussion of knowledge and its classification the reader is referred to (Ahmed et al., 2005) and (Christiaans, 1992). Such classifications of knowledge are seen by the authors as compatible with the theoretical v technological knowledge model referred to here.

1. 2 Process: intuition and analysis tools

The design process can be broadly divided into two activities, idea inception and testing. The former follows a process of 'intuition' and the latter is largely encompassed by methods of analysis in the context of structural engineering.

Although there have been recent developments to introduce some of the physically 'intuitive' aspects of computer games to structural software, including project Vasari (developed by Autodesk) and Kangaroo (developed by Rhino), software remains substantively a modeling tool for testing predesigned structural concepts rather than to generate ideas. As a result, structural engineers continue to use a range of intuitive ideas about structural behaviour in formulating design ideas. The range of intuitive approaches is open ended and can be intensely personal. Approaches include variations of bio-mimicry, for example, in which the designer imagines the structural form as a plant and visualizes where the stems would be and their relative thicknesses. (M. Cook, personal communication, September 21, 2011). Equally, intuition can be based directly on precedent, with the designer visualizing the project as a structure similar to existing built work. Some intuitions can be related directly to structural theory, such as the visualization of load paths to create an equilibrium force state in a structure or the distribution of movements and hence forces in a structure, as a result of the relative stiffness of different elements. (Brohn, 1984). Mainstone provides a most illuminating description of intuitive processes, categorizing approaches as based on observation, visualization or the feeling of force within the body (Mainstone, 1963).

Critically, the different modes of intuition incorporate a variety of ideas and assumptions about material behaviour, which in turn create a complex picture of how structural engineers understand material.

MATERIAL PRESENCE

INTUITION	<ul style="list-style-type: none">In intuition, material can be critical to concept or entirely absent
ANALYSIS TOOLS	<ul style="list-style-type: none">Analysis tools use generic material properties

PROCESS

KNOWLEDGE

TECHNOLOGY	<ul style="list-style-type: none">Material behavior fundamental to technology
THEORY	<ul style="list-style-type: none">Theory based on a generic understanding of material

Figure 1. Framework for considering material in terms of design process and knowledge

2. Research approach

Using the framework of design knowledge and process as described in figure 1, three projects were examined for the presence and nature of material understanding . By extracting specific design ideas and decisions from the documentation and categorizing them based on the type of material knowledge, (either theoretical or technological), and the process by which the decision was made, (either intuitively or using a specific design tool to verify), the authors examined the role of material in the three projects, from the perspective of the structural design.

2. 1 Project Choice and Characterization

3 projects were chosen for examination, namely:

- The Massar Children's Discovery Centre, Damascus, Syria.
- The 'Skywalks' pedestrian footbridge network, Riyadh, Saudi Arabia.
- The Institute of Diplomatic Studies, Riyadh, Saudi Arabia.

The projects were chosen on the following basis. Firstly they all had an extended design process, (minimum 1 year), with a considerable quantity of documented design information that it was possible to refer to. This was important as the objective was to study a design environment rich in decision making. In each case a large selection of design reports, email correspondence, meeting minutes, drawings and specifications were available to the authors. Also, the projects had certain similarities which encouraged a detailed discussion of structural behaviour. They all had a geometry which could be described as complex and which required sophisticated software to describe the form but more importantly, in each case the structural solution was not immediately obvious at the outset of the design process. In fact, in each case the suitability of the building envelope or 'skin' as structure was discussed at length. All the projects were a collaboration between Buro Happold Consulting Engineers and Henning Larsen Architects between 2006 and 2010. The primary author had first hand experience of all the projects.

In addition each project had unique characteristics. The Massar Discovery Centre design process was concerned with the feasibility of achieving a specific architectural form within the building culture and

technological constraints of Syria. By contrast, in the Institute of Diplomatic Studies project the structural ideas were drivers of form generation. The main architectural design concept was the creation of a central communal space or ‘oasis’ and the architects were keen for the structural and environmental technological possibilities and constraints to influence the form. In this instance, the design was developed using form-finding software and physical modeling techniques to create an optimized structural form, based on idealized load conditions. The Skywalks bridge network project had different design drivers again. In this case the architectural spatial constraints were less significant and the design process was focused on delivering a generic design which, while on the one hand was materially efficient and adaptable to the different physical constraints of the various sites, could be constructed by a number of construction techniques (to create an open and competitive procurement route) and also had a unique and striking form.



Figure 2. Institute of Diplomatic Studies



Figures 3 and 4. The Massar Discovery Centre and the Skywalk Bridge Network

2.2. Method of data analysis

The method of analysis was as follows. A total of 281 separate references to ideas or decisions regarding structural behaviour were identified in the documentation of the three projects. Henceforth, these will be referred to as structural ‘design statements’. The majority of design statements were from the structural engineering documentation but those from other design professionals including architects, building service engineers and contractors were included when they weren’t covered within the structural engineering documentation but had a structural basis. (50 of the original data set were in

fact discarded due to their lack of structural basis or repetition of ideas). The design statements were collected from a range of pre-construction phases.

Each design statement was coded in relation to the type of knowledge on which the statement was based (theoretical or technological), and its role in the design process, either as an expression of structural intuition or the documentation of the use of an analysis tool to verify an idea regarding structural behaviour. (See figure 1). The method of articulating intuition, for example by sketching or talking, was also coded. Before commencing the coding process, an extended list of sub-codes had been established based on a literature search and previous interviews, to further divide the various categories. This was used as a starting point, and during the coding process, this was modified in response to the data being analyzed. Unused categories were removed. It should be stressed that the sub-coding process was used in this context to allow the observation of patterns of design thinking, rather than a process of classification and as such was continually under review. In fact, the original pass at coding and sub-coding was reviewed in full after 6 months and some small changes made. A total of 27 sub codes were recognized in the 3 projects and are outlined in table 1.

Following completion of the coding and sub-coding process, the data was presented in terms of the relative frequency of the different categories of knowledge, process and method of articulation. This was undertaken for the full data set (figures 5, 9 and 10) but also split up by project phase, individual project and the profession of the designer. Correlations in the data set were also examined. The frequency of cases in which specific sub-codes of knowledge, process and method of articulation were present in the same design statement, was analyzed.

It should be noted that the analysis does not take into account the relative importance of each design statement in developing the overall project or the time it took, or indeed the quality of the design decisions made as a result. Also, the number of design statements varied based on the richness of the data set. The Masser Children's Centre had the largest data set of 107 design statements, while the Institute of Diplomatic Studies and Skywalks project had respectively 55 and 79 design statements.

PROCESS		KNOWLEDGE	
Intuition Categories – Design Inception (IC)		Technological Knowledge (TEC)	
IC1A	Load Path/Equilibrium Concept	TEC1	Material Based Technology
IC1B	Relative Stiffness Concept	TEC2	Empirical Testing as Design
IC2	Observation of Precedent	TEC3	Design by Components
IC3	Biological Analogy	TEC4	Ideas from Cultural and Historical Context
ICA	Abstract Concept- (<i>Idea generating form</i>)	Theory of Structures and Strength of Materials (T)	
Mathematical Tools- Verification (TM)		TS1	Geometrical Load Path (Tension and Compression)

TMH1	Hand Calculations based on Force Distribution	TS2	Beam and Frame Load Distribution
TMH3	Hand Calculations based on Elasticity	TE	Theory of Elasticity (and extensions to the Theory of Elasticity)
TMN1	Software Calculations based on Force Distribution		
TMN3	Software calculations based on Elasticity		Method of Intuition Articulation (IM)
TMN4	Software Calculations based on Inelastic Behaviour	IM1	Hand Sketching
TMT3	Tabulated Solutions based on Elasticity	IM2	Noting
TMT4	Tabulated Solutions based on Inelastic Behaviour	IM3	Talking
Physical Models –Verification (PM)		IM5	Images
PM1	Form Finding Models	IM6	Computer Sketching

Table 1. Process, Knowledge and Method of Articulation Sub Codes

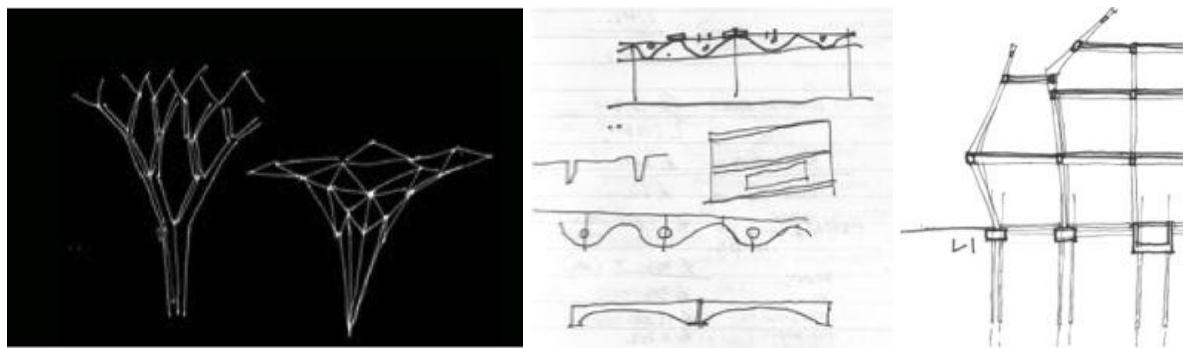
3. Findings

3.1 ‘Method of articulation’ data set

The data set indicates that the majority of design statements are articulated either by sketching by hand (IM1) or through discussion (IM3) in the design team, primarily at meetings, although there are a number of other methods used (Figure 8). Sketching using a computer is not very prevalent (IM6), although its incidence is higher in the Skywalks bridge project due to the specific personalities in that design team. The frequency with which design statements are articulated using words (written or verbally) is relatively constant through the various project stages, an indicator of a continuing dialogue within the design team and with the client in each project. By contrast the use of images, reduces dramatically after the first stage in all the projects as the design becomes more concrete. The use of sketches peaks at concept and detailed design stages, corresponding to the stages of most rapid design development.

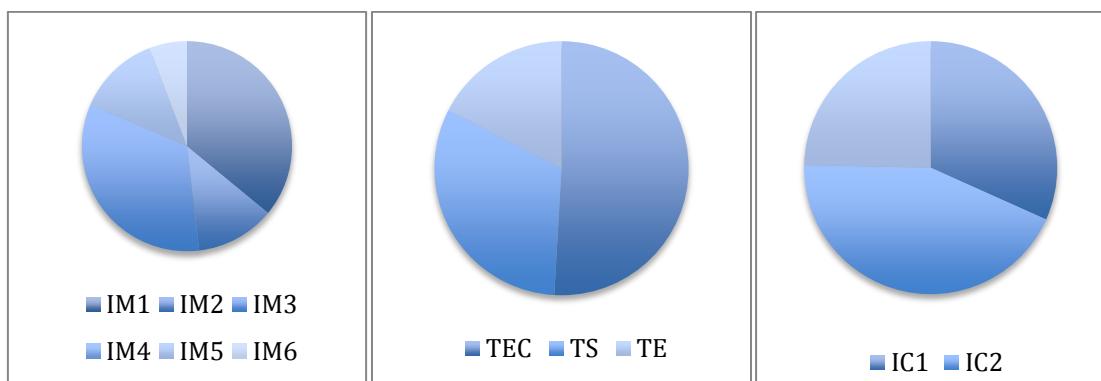
A significant majority of the design statements described by images and through discussion, articulate intuitions based on precedent and refer exclusively to technological knowledge. In the case of images 70% and in the case of discussion 81%. By contrast, the ideas articulated by sketching can be based on the theory of structures or technological knowledge or indeed both which highlights the adaptability of hand sketching as a design tool, and the often complex interaction between the theory of structures and technological knowledge. More specifically, of the ‘sketch’ data set, 28% of the design statements are

based on technological knowledge only and exclusively articulate a process of intuition based on precedent while 38% of design statements refer to knowledge founded on the theory of structures and articulate a process of intuition based on mathematical systems including equilibrium, relative stiffness or a mechanism. The remaining 25% of design statements are based on both technological and theoretical knowledge and articulate a mixture of intuitions. Examples of these three types of sketch are shown in figures 5, 6 and 7.



Figures 5, 6 and 7. Sketches indicating various knowledge sources: Theory of Structures only, Technology only and Combined Theory of Structures and Technology.

Examples of each of these sketch categories can be seen in all stages of each project's design process with the exception of certain early stages of the Institute of Diplomatic Studies, where the mixture of technological and theoretical knowledge is absent. This would appear to be due to the 'abstract' design process chosen as discussed previously.



Figures 8, 9 and 10. Complete Data Sets: Method or articulation, Knowledge and Process.

3.2 Knowledge data set

Figure 8 reveals that 52% of the design statements depend on technological knowledge (TEC) rather than theoretical knowledge (TE and TS). The authors would argue that this large presence of technological knowledge indicates a frequent consideration of material behaviour in the projects. This proportion decreases from approximately ¾ of design statements at the feasibility stage to a 1/3 as the projects progress to completion. Material and component based technological understanding is consistently present through all stages of each project but technological knowledge which is more

loosely based on the cultural or historical context, appears to reduce significantly as the projects progress. In the complete data set, technological knowledge appears to closely relate to intuition based on precedent. 90% of design statements with intuition from precedent are based on technological knowledge rather than the theory of structures.

Technological knowledge is strongly present through all the projects but it was particularly noted that material knowledge remained very dominant throughout the Skywalks bridge design project due to the need to develop a design which promotes an ‘open’ technological procurement route compatible with the full range of steel connection and erection technologies available. Similarly, in the Massar Children’s Discovery Centre material technology is very prominent due to the detailed discussion regarding the specific construction context of Syria. It should be noted that the designers involved in all the projects, who were not structural engineers, used almost exclusively knowledge based on technology highlighting the particular disciplinary nature of the theory of structures. However, it should be pointed out that designers other than structural engineers only account for the generation of 9% of the data set.

Of the design statements founded on theoretical knowledge, 58% specifically relate to theory in which constituent material parameters plays no part. The remaining minority of statements are based exclusively on elastic theory or extensions to it, in which the Young’s Modulus, as a measure of material stiffness, is used. The statements which are based on elastic theory are primarily analyses of movement or buckling behaviour and are more prevalent towards the end of the projects. The prevalence of elastic theory does vary between projects, based on the specific problems being tackled. For example, in the Skywalks bridge project, problems which required a value of Young’s Modulus for analysis, are only present towards the latter stages, as the form of the structure was almost exclusively generated based on an understanding of force distribution. This highlights that elastic theory is useful to quantify specific problems but is not the only tool of choice of structural engineers.

3.3 Process data set

Figure 9 indicates that 25% of the design statements are based on a process of verification or testing™, leaving the vast majority depending on intuition (IC). The dominant processes of intuition were as follows: 42% of the total of design statements were informed by an intuition based on precedent (IC2) and 32% on mathematical concepts of relative stiffness, equilibrium and mechanisms (IC1). The authors would argue that strong representation of precedent demonstrates a high presence of material consideration in these design projects.

Examples of intuition based on precedent reduce progressively from about ¾ to 1/3 as the projects progress while those based on mathematical concepts are relatively constant. By contrast, the number of design statements based on a process of verification or testing gradually increases as the projects progress, which would be consistent with an increased requirement for checking and verification as the design becomes more detailed. The Institute of Diplomatic Studies project has uniquely the presence of form finding techniques based on an efficient distribution of force, both using physical and mathematical modeling tools. Intuition based on biomimicry was also used on this project. Such processes, using an abstraction of material as ‘matter’, promote a generic rather than a particular understanding of material.

4. Conclusions

Looking at the data as a whole, it is clear that the variety of ideas and techniques available to structural engineers to understand materials is extensive. On the one hand, simple techniques based on the theory

of structures allow quantitative testing of problems using basic material properties as ‘matter’. On the other, ready access to knowledge of the particularities of individual materials and technologies promotes their sophisticated use in design. With regard to the latter, it was noteworthy the dominance of material technology and precedent in the data set and hence the authors would argue a high consideration of the understanding of specific materials.

However, the data from these three projects indicates more complex patterns regarding how this knowledge is combined, than this simple opposition suggests. On the one hand images, appear to articulate the idea of technology in isolation, as does discussion. By contrast, the traditional technique of hand sketching is suited to the articulation of both technology and the theory of structures, often both at the same time demonstrating that in many situations the understanding of the theory of structures and technology and therefore the representation of material is interwoven in a complex manner in the mind of the engineer. This inevitably raises the question whether contemporary computer sketching techniques have the same level of sophistication as a tool for expressing ideas. The data set on these projects was not sufficient to conclude on this manner.

As a general comment on the design process of these projects, it is noteworthy the wide range of problems encountered and by necessity the requirement for expedient techniques and approaches to solve problems quickly. This can be seen in the prevalence of intuition, simple methods of analysis and the direct reference to specific materials, through technological knowledge and precedent. This conclusion reflects the observations of Vicenti (1990) that most design decisions are a process of satisfaction rather than optimization, given their sheer number and complexity.

To conclude the authors wish to point out that this is a study of specific design teams in unique companies with a strong design culture. As such, the conclusions do not necessarily have general applicability for industry. However, it is anticipated that the conclusions are being used to inform a series of semi-structured interviews with a wider range of practitioners to place the issues in a wider context as a second stage of research.

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