ELSEVIER

Automation in Construction 16 (2007) 45 – 53

AUTOMATION IN CONSTRUCTION

www.elsevier.com/locate/autcon

Rationalising bubble trusses for batch production

Thomas Fischer *

Spatial Information Architecture Laboratory, RMIT, Melbourne, Australia
School of Design, The Hong Kong Polytechnic University, Hong Hum, Kowloon, Hong Kong, China

Abstract

This paper is a progress report on an investigation into the rationalisation of apparently irregular, foam-like space frame structures. The notion of design rationalisation and its background are introduced and three alternative approaches to it are demonstrated and examined. One of the three approaches, that of co-rationalisation, has received attention only recently. Since it appears to offer interesting possibilities for integration into design processes, co-rationalisation is explored and analysed in greater detail. The paper concludes with some observations made in the discussed rationalisation processes. They suggest a possibility of generalisable related knowledge and of systematic design decision support for design rationalisation beyond the immediate context of foam-like space frame structures.

Keywords: Rationalisation; Truss structures; Prefabrication; Apparent irregularity; Generative design

1. Introduction: Rationalisation strategies

As new building forms tend towards increasing complexity [1], building activity continues to be subject to economic constraints and pressure for cost-efficiency [2]. As architects are increasingly engaging in digital practice, they tend to increase buildings' complexity while at the same time mitigating the associated high cost of fabrication. A typical result of complex building designs, and also a significant cost factor, is the increasing number of different required building elements. While traditional brick houses for example can be built from a single type of brick and while a modernist office building can potentially be built using a single type of facade panel, irregular architectural form often times requires hundreds or more different building elements. The 2001 courtyard extension of the British Museum in London (Foster and Partners) for example is reported to be comprised of some 6000 individual steel members and 1826 individual connecting nodes [3]. In response to this increased variation in built form, new digitally supported design and construction strategies such as computer numerically controlled (CNC) fabrication of unique components are increasingly deployed. Aiming to produce irregular designed form by more affordable means, it has also become a common practice in the planning of complex building form to devise shapes that, to an onlooking observer, appear irregular in some ways, but which are constructed from few sets of identical building elements and which are configured in seemingly or actually non-periodic assemblies. The latter approach has been exemplified in a number of recent projects and publications including for instance the quasi-repetitive packing structures presented by Marta and Grima [4]. This approach is known as design rationalisation and it can generally be defined as the process of approximating an intended form with a well-defined generative principle in order to facilitate building execution.

This paper examines the possibilities of rationalising apparently irregular form to the extent that the numbers of required identical building elements is maximised so as to allow the harnessing of the economic benefits of batch production. The scope and objectives of rationalisation work can however extend beyond the cost benefits offered by batch or mass production. Rationalisation can for instance also aid in compliance with geometric constraints imposed by manufacturing machinery, at structural performance optimisation or at the mere generation of coordinate data for construction purposes. In differentiating ways of making form into the domains of construction and assembly of composite structures on one the hand and forming of raw materials by means of moulding, cutting and subtraction on the other, rationalisation of irregular building form currently has a strong focus on

* School of Design, The Hong Kong Polytechnic University, Hong Hum, Kowloon, Hong Kong, China.
E-mail address: sdtom@polyu.edu.hk.

0926-5805/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.autcon.2005.10.004

construction, in particular in terms of prefabricated building elements. The recently increasing number of challenging architectural projects involving visual irregularity and requiring rationalisation such as the Beijing Olympic Stadium (Herzog and De Meuron) or the Kunsthaus in Graz (Peter Cook and Colin Fournier) are examples of constructed complex forms. Rationalisation is however as applicable and as useful to processes of forming, that is, to moulding and subtraction-based form finding as it is to constructed assemblies. Gaudí's rationalisation of curved-surface geometries for the Sagrada Família Church are compelling examples [5].

The aim of rationalisation in the investigation presented here is to find descriptions of and generative procedures for apparently irregular space frames. Apparent irregularity has been defined as allowing an observer to make only general statistical statements when predicting the composition of an unknown part of a structure on the basis of a known part ([2], p. 231). Space frames are understood and modelled as consisting of two types of components, namely struts and nodes. To achieve visual irregularity, the investigated structures require some level of variation of strut lengths and node connection angles in contrast to the uniformity found for example in Fuller's highly regular *octet truss* space frames (see Ref.[6], p. 2). While preserving overall irregular appearance, rationalisation should allow variations to be minimised in order to support cost-efficient production of batches of identical components.

Design rationalisation, while aiming at reducing the number of different building elements, does not however necessarily aim at total standardisation by fully eliminating unique elements. As Lindsey ([7], p. 71) reports of the Gehry Partners practice, unique building components remaining in a rationalised structure do not necessarily contradict the intention of rationalisation. Rather, the office aims to reduce the percentage of unique components below a certain threshold relative to the proportion of batch-produced, interchangeable elements so that the cost-savings offered by batch production of non-unique elements compensates for the higher cost of unique ones (see also Ref. [8], p. 28). Hugh Whitehead of the Foster and Partners' Specialist Modelling Group is credited with introducing a distinction between alternative rationalisation approaches. A 2003 master's thesis ([9], pp. 32–33) cites Whitehead's distinction between pre- and post-rationalisation, while more recently Whitehead is reported to have extended this categorisation to now differentiate between pre-, co- and post-rationalisation [10]. Pre-rationalisation describes a process in which the compositional system is defined before the actual design process. Co-rationalisation describes a process in which the compositional system is defined alongside and to some extent through the process of designing a form. Post-rationalisation takes a designed form and imposes a compositional system onto it retroactively.

This study examines applications of these three alternative approaches to the problem of rationalising space frame structures designed to convey a visual appearance similar to that of liquid foam. This task has recently been tackled in the design of the Beijing National Swimming Centre (PTW, ARUP and the China State Construction Engineering Corporation). For this project, ARUP engineers in Sydney have approached the rationalisation problem by making use of an existing geometric principle. It is based on a close-packing of polyhedra presented by Weaire and Phelan [11], containing equally sized polyhedra with minimal surface per volume [2]. It was presented as a more efficient response to the so-called *Kelvin Conjecture*, a close-packed structure of truncated cuboctahedra [12]. The discovery of this slightly more efficient solution to the problem has taken 106 years, despite the fact that many have been searching for more efficient solutions. When identifying this structure and its high surface-to-volume efficiency, Weaire and Phelan were in fact looking for something else (see Ref. [13], p. 183). This illustrates the absence of formal methods for identifying lattices or polyhedral packings that satisfy given sets of requirements or criteria than those posed by design rationalisation tasks. By the same token, there is a lack of a methodology for proving or disproving the existence of lattices or packings for which geometric criteria constraints are given. This absence of methodology and the resulting necessity for open-ended puzzle solving seem to be typical for design rationalisation, and finding a previously identified geometric principle as in the case of the Beijing National Swimming Centre can be a stroke of luck. The structure used in the Beijing project is by the way not quite the actual Weiare–Phelan structure. The Weiare–Phelan structure is the basis for this geometry, which is subsequently evolved into a more tension-efficient derivation with curved edges a system that would be more difficult to construct physically. The choice of the Weiare–Phelan inspired packing structure initially promised an extremely high degree of rationalisation of the originally proposed appearance of natural foam. As Bosse [12] reports, the chosen structure contains only four different strut lengths and three different node types. The final design of the building however turned out to contain hundreds of different strut types, mainly due to the at interior and exterior building walls cutting through the foam structure, but also due to varying strut diameters, which are the result of weight and structural performance optimisation. As a consequence, this instance of foam truss rationalisation does not allow cost-efficient batch production of identical, interchangeable building elements and does not yield significant economic benefits. Moreover, constant bubble volumes such as those in Weaire–Phelan foam are not typically found in natural, irregular foam, which has a high degree of variation in bubble volumes. These two points have prompted this investigation of alternative rationalisation strategies for apparently irregular, foam-like space frame structures.

2. Applying all three strategies

This section presents some approaches to the challenge of rationalising apparently irregular, foam-like truss structures, exemplifying the three alternative rationalisation strategies outlined above. After discussing some issues related to topological composition and experimental strategies, it gives an account of a pre-rationalisation approach followed by a post-rationalisation approach. The development of a co-rationalisation approach has been particularly challenging but