Automation in Construction 63 (2016) 57–65

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Quilt pattern inspired engineering: Efficient manufacturing of shelter topologies

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ARTICLE INFO

Article history:
Received 12 May 2015
Received in revised form 27 October 2015
Accepted 6 December 2015
Available online 23 December 2015

Keywords:
Shelter
Structural morphology
Manufacturing
Sandwich panel
Lightweight structure
Temporary structure

ABSTRACT

Lightweight, thermally insulated, temporary shelters are essential for disaster relief and military operations. To minimize cost and increase sustainability, it is advantageous to reduce wasted material in manufacturing these shelters. This paper investigates quilt patterns – designs of interlocking geometric shapes – as inspiration for structural topologies that can be manufactured from flat sheets with minimal wasted material (shape interfaces serve as cut and fold lines). A series of quilt-inspired concepts based on established quilt patterns are developed into structural topologies using shape grammar rules. The detailed finite element analysis and design of three concepts is presented. To achieve a lightweight, thermally insulated design, the structures are comprised of sandwich panels (fiber-reinforced polymer faces and a foam core). The performance of each design is compared to an existing rigid wall shelter, demonstrating the efficacy of quilt-inspired forms. This paper is the first investigation of quilting as inspiration for structural systems.

1. Introduction

Developing lightweight temporary sheltering systems that are thermally insulated is critical for military and disaster relief efforts. Thermal insulation in shelters is an increasing priority for the military due to fuel costs for heating and air conditioning shelters and lives lost in fuel transportation missions. For example, as of 2011, the United States military is spending 66 million USD per day on fuel for air conditioning and over one thousand soldiers have been killed in fuel missions in Iraq and Afghanistan [1]. Furthermore, with an expected five-fold increase in the number of natural and anthropogenic hazards within the next 50 years [2], improved sheltering systems are an increasing humanitarian priority as well. Existing soft wall (canvas) shelters are inexpensive, lightweight, and can be packaged in small volumes for transportation. However, they provide limited thermal insulation. Rigid wall shelters offer high thermal insulation, but are heavy and difficult to transport. In addition, they tend to be box-shaped topologies which are not structurally efficient. See Quaglia et al. [3] for a detailed review of these systems.

Energy efficiency and modeling of temporary sheltering are becoming an increasing area of research (e.g., [4–8]). Toward addressing the challenge of increasing the thermal insulation for temporary shelters, the development of novel shelter topologies is a growing field. Ongoing research activities include investigating the implementation of structurally insulated panels (SIP) for military barracks [9–10]. The art of origami offers inspiration for a wide array of engineering applications [11], particularly for thermally insulated, deployable sheltering topologies as it offers a means for packaging rigid wall shelters in small volumes [12]. Quaglia et al. [3,4] have proposed a viable solution for a deployable origami-inspired shelter with enhanced energy performance that has been experimentally tested [13–14]. This solution is comprised of sandwich panels [fiber reinforced polymer (FRP) faces and a foam core] which offer a high strength-to-weight ratio and thermal insulation for energy efficiency in heating and cooling [4,12]. When using high cost materials such as advanced composites, however, there is an advantage in minimizing wasted material in the manufacturing process. An additional advantage of origami-inspired engineering is that it is based on using only a single sheet of material, i.e., waste of material in the manufacturing process is minimized. Alternatively, when deployability is not required and a rigid wall sheltering system can simply be erected in-situ from prefabricated panels, the art of quilting can be used as inspiration for novel, structurally efficient topologies that minimize wasted material in manufacturing. More specifically, quilt patterns are carefully designed, interlocking geometric shapes that form a single surface known as a quilt block. The resulting pattern could be utilized as a manufacturing pattern in which shape interfaces serve as lines to cut flat sheets of material.

At the most basic level, a quilt can be defined as being comprised of two pieces of fabric that are stitched together separated by padding. Quilting includes both the art of needlework to stitch independent fabric pieces together and the art of patchwork which determines the

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http://dx.doi.org/10.1016/j.autcon.2015.12.005
0926-5805/

shape and colors of pieces to be combined. Quilts can be classified into three categories: pieced, appliqued, and quilted counterpane [15]. Pieced quilts – comprised of fabric pieces cut into prescribed shapes and stitched together [15] – are the focus of this research and it is the art of patchwork from which the structural topologies will be derived. The history of quilting in the United States and England can be traced to access to Indian calico fabrics and quilts toward the end of the 18th century. These washable cotton fabrics featured new ranges of colors and patterns than were previously available in these regions and stimulated the textile industry to begin making similar fabrics. Any unused pieces of fabric were deemed valuable and were saved for quilting. From these early inspirations, quilting was embraced throughout the United States and was adopted as a central activity for 19th century American women. Beyond fulfilling a functional need, quilts became a means of artistic expression, even being used for political messages. Quilting became a unique, American form of art [16]. Pieced quilt patterns have been developed and evolved over centuries with varying names and attributions [17]. While patterns have been published in various magazines since the early 19th century [17], these patterns developed outside of the traditional framework of authorship, intellectual property, and copyright protection [18]. As a result, the quilt patterns discussed in this paper are not attributed to an author and are referred to by traditional names. This paper will develop structural topologies based on established quilt patterns.

This paper proposes quilt-inspired engineering as a strategy for generative structural design for temporary military or disaster relief sheltering aimed toward manufacturing efficiency. Incorporating manufacturing and constructability priorities in the development of structural forms is an active area of research using many approaches. Topology, shape, and size optimization [19] methodologies are increasingly being developed to consider these priorities, including for example fabrication cost [20], construction cost [21], and manufacturing constraints [22]. Optimization methodologies are also being implemented for the design of modular structures which offer cost-saving through opportunities for mass-production [23]. Alternatively, shape grammars – a formal computational approach to generate geometric forms [24] – can be utilized to develop novel architectural topologies [25]. However, this approach can generate an infinite number of

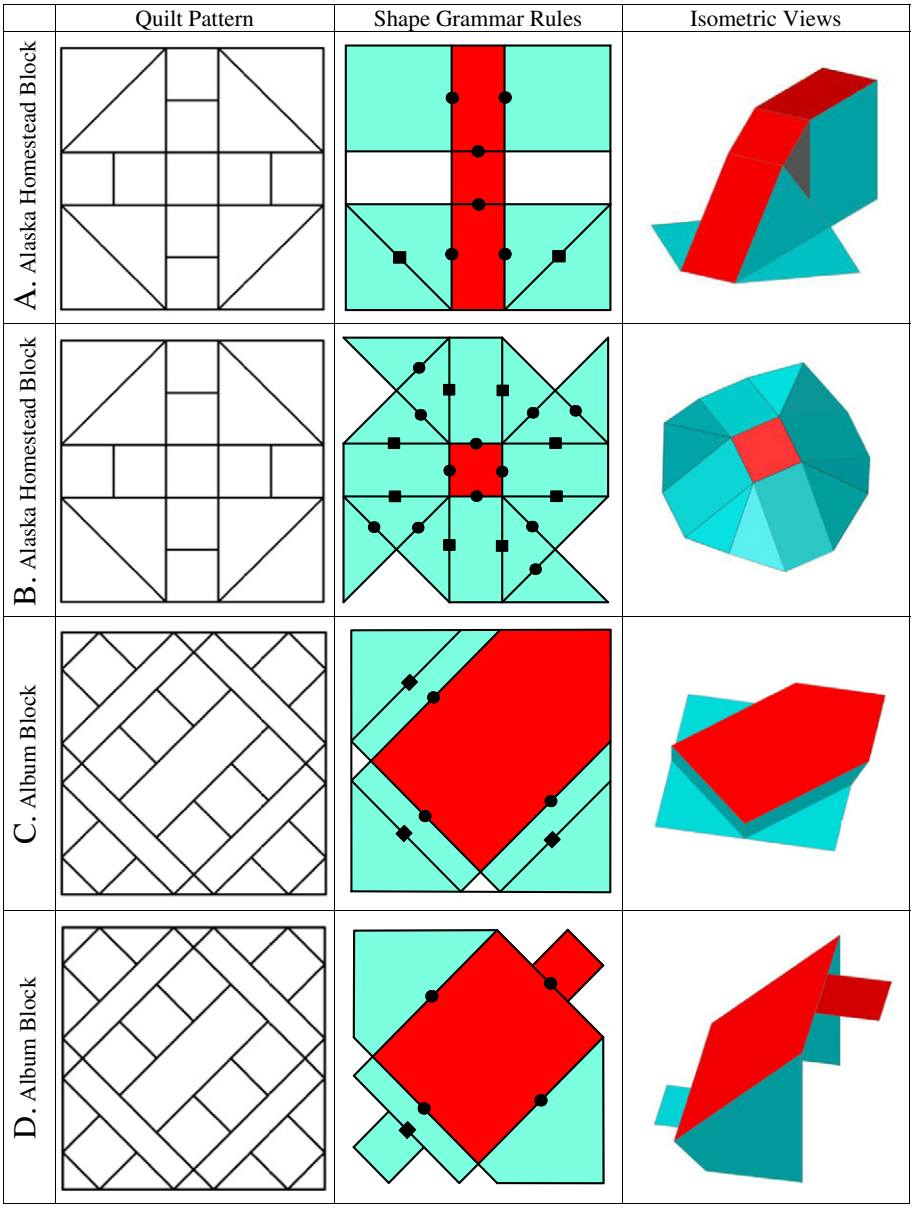

Fig. 1. Quilt-inspired concepts, including the established quilt pattern (including name), functional and three-dimensional shape grammar rules implemented (two-dimensional rules not shown for simplicity), and isometric views of the three-dimensional structures.