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Balancing energy efficiency and structural performance through multi-objective shape optimization: Case study of a rapidly deployable origami-inspired shelter☆

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ABSTRACT

For military and disaster relief housing, rapidly deployable shelters must be lightweight, be packaged in a small volume for transportability, and be erected without heavy lifting equipment. A critical design criterion is also energy efficiency in heating and cooling. To meet these priorities, the research team has utilized origami as inspiration for a thermally insulated rigid wall deployable shelter that can be erected manually through counterweighting. To enhance energy efficiency, improvements in the shape of a structure (i.e., member lengths and angles) at a design stage can lead to savings throughout its lifecycle. This is magnified in the context of mass-production of deployable shelters, where any improvements are multiplied. Structural efficiency is also critical to achieve lightweight design. This paper presents a multi-objective shape optimization methodology which balances the priorities of structural performance (i.e., minimum deflections) and energy efficiency (i.e., minimum thermal energy load). This is demonstrated for the case study of a deployable shelter. Design variables include geometric parameters. Constraints relate to the package size and capability of interfacing with existing technologies. Structural analysis is performed using a parametric finite element program. Thermal energy is calculated using EnergyPlus. An optimized solution is found and compared against existing military solutions.

1. Introduction and motivation

Standard design priorities for rapidly deployable shelters in military or disaster relief applications include adequate structural performance, a low self-weight, a small package volume, and ease of erection. A rising priority, particularly within a military context, is reducing fuel consumption for heating and cooling these shelters. The US military currently spends 66 million USD per day on fuel for air conditioning (24 billion USD per year; data as of 2011) [1]. This is due to both the cost of fuel itself and the cost of transportation and security for fuel missions [2]. More specifically, while the standard cost of a gallon of generic diesel fuel in 2014 is 3.25 USD [3], the fully burdened cost of fuel, which includes security and transportation in a military context, can be up to 600 USD per gallon [2,4]. As of 2011, one thousand Americans have died during fuel missions in Iraq and Afghanistan [1]. This data demonstrates the urgent need for sheltering systems that can meet structural and deployability requirements while reducing fuel consumption.

Existing military sheltering systems (see Fig. 1) include soft wall (canvas) and rigid wall solutions (see [5] and the review in [6]). Soft wall shelters feature excellent deployability (including low self-weight and small package volume), but provide little thermal insulation. Energy for heating and cooling can be reduced by 80% in such shelters through the application of spray foam insulation [1]. However, this prevents such shelters from being re-deployed. Alternatively, rigid wall shelters provide higher thermal resistance, but have large self-weights and package volumes. Toward achieving the standard design priorities and integrating energy efficiency, Quaglia et al. [6] have proposed an origami-inspired deployable shelter (see Fig. 2) known as the Lever Shelter Module (LSM). Here, the art of origami is employed as inspiration for folding a rigid wall system. It can be packaged small (Fig. 2(A)) to be transported on a standardized 463L pallet [7] making it transportable by air, truck, rail, or ship. The folding rigid walls are comprised of sandwich panels which have a high strength to weight ratio (resulting in a low-weight shelter) and offer high thermal insulation [8]. A novel erection strategy utilizing a lever arm which can rotate the shelter into a self-supporting position (Fig. 2(A)–(D)) enables the

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☆ This document is a collaborative effort.
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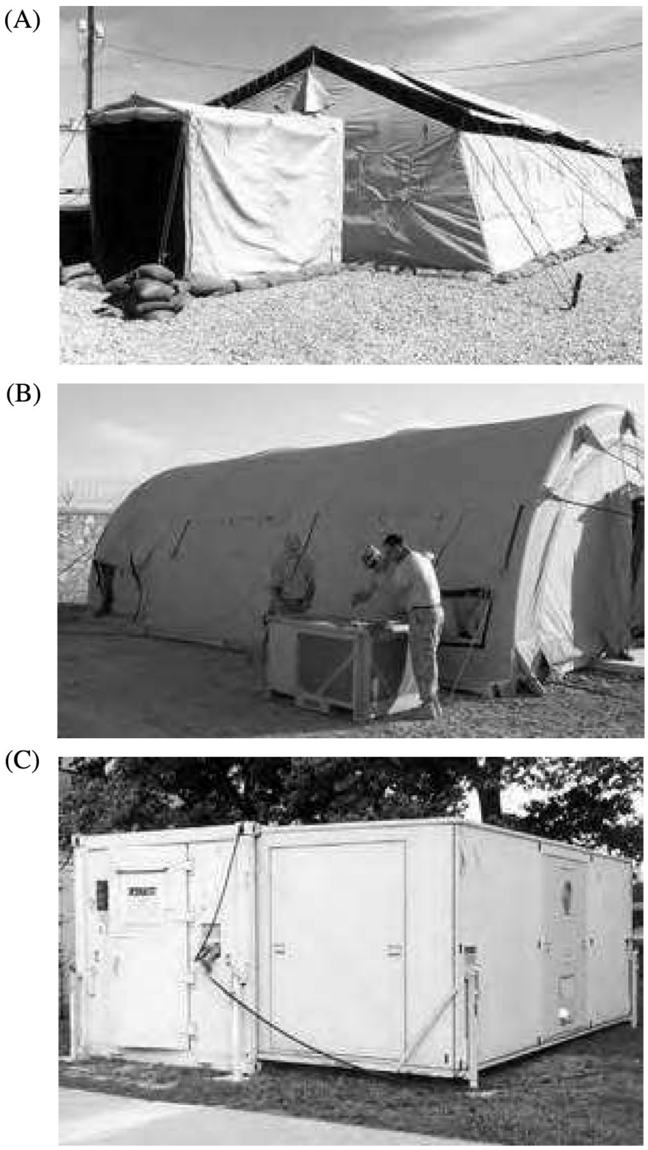

Fig. 1. Existing military shelters, including (A) soft wall TEMPER tent, (B) soft wall TEMPER Air tent and (C) a rigid wall shelter.
Images courtesy of [5].

system to be erected without the use of heavy lifting equipment. The shelter is highly modular (Fig. 2(E) and (F)) for versatility of use and can be interfaced with existing military technologies by Force Provider [9], including kitchens and latrines, housed in Tricon shipping containers [10]. This concept provides the deployability needed to meet transportation goals while also offering thermal insulation [6]. While the thermal insulation provided through sandwich panels increases the energy efficiency of the shelter system, the design of the shelter itself can also be developed toward this goal. This paper presents a multi-objective shape optimization of the LSM for structural performance (i.e., minimum displacement under service loads) and energy efficiency (i.e., minimum thermal energy load to maintain the shelter within a temperature range for one year).

Shape optimization of structures for energy efficiency (i.e., optimization of the global structural form toward reducing the fuel needed for heating and cooling) is a powerful design tool for the sustainable building community since any reduction in fuel consumption made through design is multiplied over the lifecyle of this structure. This is especially significant for the case of deployable structures for military and disaster relief applications where such designs are also mass-produced. A wide body of research is developing in the study of the effects of different structural characteristics on the energy efficiency of a structure. The most relevant examples are briefly reviewed here. Multi-objective optimization of the shape of a building for minimum building cost and for minimum yearly heating cost has been investigated by Adamski and Marks [11] and Jedrzejuk and Marks [12] for octagonal plans, by Adamski [13] for arbitrary plans defined by two curves, by Marks [14] for arbitrary and polygonal plans, and by Adamski [15] for oval plans. Bouchlaghem [16] demonstrates a procedure for optimizing shading devices for minimum cooling load of a building. Caldas and Norford [17] optimized window size for lighting, heating, and cooling. In later work, Caldas and Norford [18] also optimize (1) building materials for minimum energy consumption and initial building cost, (2) building form for lighting and heating energy, and (3) Heating, Ventilation, and Air Conditioning (HVAC) system size, control strategy, and building envelope for minimum energy cost. Coley and Schukat [19] have proposed a procedure to optimize the shape (building perimeter and roof pitch) and construction details (e.g., materials, window location, orientation) to identify a broad range of low-energy designs that can then be assessed for their architectural appeal. Grierson and Khajehpour [20] presented a methodology for optimization of commercial buildings for minimum capital and operating cost (including cost of energy, maintenance, and taxes) and maximum income. Design variables include the structural system, the floor system, cladding type, window type, window ratio, number of bays, and bay width. Here, structural performance is included as each conceptual design is analyzed for load-path redundancy to prevent against progressive collapse. Michalek et al. [21] propose a method to optimize the floor layout of a building for energy, lighting, wasted space, access ways, and hallway objective functions. Malkawi et al. [22] optimized building shape (i.e., length, width, and height of an orthogonal geometry, window location and size, position and size of supply and extract terminals) to maximize thermal and ventilation priorities. Wang et al. [23] optimized the building orientation, aspect ratio, window type, window to wall ratio, and material composition of the roof and walls for minimum life cycle cost and minimum life cycle environmental impact. This work is extended for the same objective functions in Wang et al. [24] with design variables including the plan shape of the building, the structural system, building envelope configurations, and overhangs. Shea et al. [25] optimize building panel envelopes for lighting and for cost. Diakaki et al. [26] proposed a multi-objective approach to optimizing the window type, wall insulation material, and wall insulation thickness for acquisition cost and energy savings. Yi and Malkawi [27] optimize complex geometries (implemented by agent nodes) for energy performance. Fialho et al. [28] use a multi-objective evolutionary algorithm to investigate the effects that changing materials and orientations of the building have on the construction costs and energy efficiency of the building. Krem et al. [29] presented a study of the effect of the position of the structural core/wall and shape of the floor plan on energy and structural performance of high rise buildings in various climate zones. Vergauen et al. [30] studied the effects of changing geometry and kinetic parameters of origami-based facade components on direct solar radiation, daylight, and glare. Martinez-Martin and Thrall [8] presented a simplified optimization methodology for the selection of the material properties of sandwich panels (i.e., material type and thickness for the face and core) for origami-inspired deployable shelters based on the competing objective functions of weight and thermal insulation. Flager et al. [31] employ Process Integration Design Optimization (a suite of software products typically used in the aerospace industry) to optimize the orientation, length, width, and member section properties of a steel frame