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Deployable scissor arch for transitional shelters

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ABSTRACT

Disaster relief shelters must be transitional, meaning capable of serving an affected community from emergency, to rehabilitation, to reconstruction. Deployable scissor structures are well-suited for this application since they are lightweight, can be compactly packaged, and have a high volume expansion ratio. Their constitutive parts can be reused and reconfigured to facilitate rehabilitation and reconstruction. This paper presents a preliminary concept for a deployable scissor shelter, including its design, analysis, and experimental validation on a full-scale prototype. First, the conceptual design and analysis using a parametric finite element method are presented. Testing of the prototype is then employed to evaluate the deployment process, support conditions and stiffening elements. Experimental data from these studies validates results from the finite element model, suggesting that the modeling tool is effective for the design of transitional shelters. A final design is presented which meets the requirements of the European Standards.

1. Introduction

In the aftermath of a natural or man-made disaster, the typical sheltering response by governments and international humanitarian organizations has been the distribution of tents or kits of basic shelter materials and tools (e.g. plastic sheeting and hammers). This response has many advantages including speed and, for appropriate kits, flexibility. But it is not intended to offer shelter over the long term. The usual lifespan ranges from a few months to two years. The lack of adequate shelter over the entire reconstruction period impacts negatively upon health and livelihood, thus constraining reconstruction and recovery [1]. However, if shelters are transitional – meaning capable of being disassembled, upgraded, reused, relocated and recycled in different configurations for alternative functions – they offer the opportunity to link relief and future development perspectives towards a sustainable solution (Fig. 1) [1–3]. Transitional shelters therefore offer the potential to not only provide shelter for displaced families, but also to facilitate personal, social and economic recovery through fulfilling functions throughout the relief and development process: from emergency, to rehabilitation, to reconstruction. This transformational capacity and the reuse potential of individual components make transitional shelters more sustainable over their life-cycle than conventional solutions which become obsolete, are often removed, disposed of, or abandoned when a transition is made from one relief phase to the next. The transitional shelter approach has been adopted, since its introduction by staff from Shelter Centre in 2005, by numerous humanitarian agencies (e.g. International Organization for Migration, International Federation of Red Cross and Red Crescent Societies) and has sheltered many millions of people worldwide (e.g. after the Sri Lanka tsunami in 2004, Haiti earthquake in 2010) [1]. Towards contributing to this transitional shelter approach, this paper presents a preliminary concept for a shelter comprised of scissor arches, including its design, analysis, and experimental validation on a full-scale aluminum prototype (6 m span, height-to-span ratio of 0.5, Fig. 2).

One of the features of emergency sheltering, which is continuously subjected to improvement, is distributing good quality shelter items which survive the end of the predicted lifetime. This is not always obvious, and certainly not in case of disasters with a larger risk of secondary hazards (such as earthquakes or hurricanes) [4]. An important example is the January 2010 Haiti earthquake, for which one of the two single largest international emergency shelter responses took place [5]. In the four months following the earthquake, up to 752,000 basic shelter items (tarpaulins, tents, kits) were distributed, but many vulnerable families remained displaced with poor shelter into 2011 and beyond [4]. To contribute to this urgent need for transitional sheltering, this paper presents a preliminary concept for a barrel arch comprised of scissor-like elements (SLEs, Figs. 2–4). SLEs, comprised of three-noded rigid bars connected at their ends and at intermediate points (Fig. 3), are single degree-of-freedom mechanisms which have widely been used in deployable structures. Scissor structures are well-equipped for

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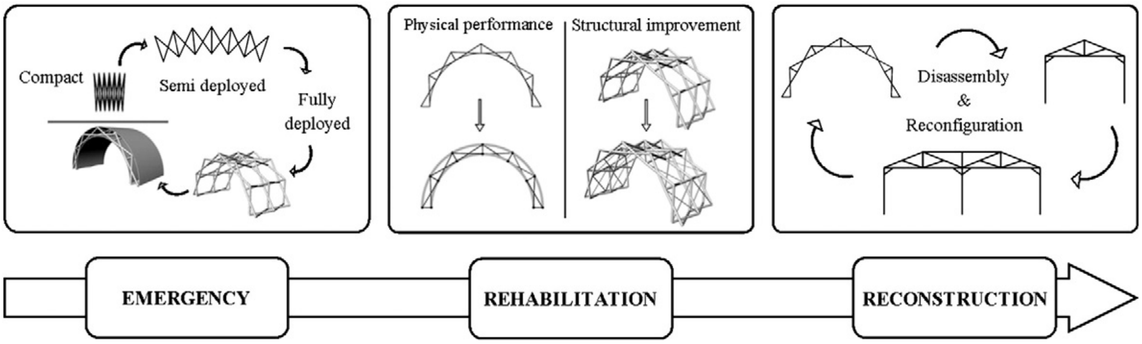

Fig. 1. Graphic representation of the three consecutive phases of relief and the proposed principles for technical solutions for transitional sheltering.

rapid deployment in the immediate aftermath of a disaster: they are lightweight, can be compactly folded to facilitate transport, and demonstrate a significant volume expansion [6–8]. Furthermore, the scissor elements can be reused in different configurations to serve the community throughout the recovery process, while adaptation is possible for different types of disasters (e.g. adding components and/or stiffening elements to enlarge the shelter to adapt to different functions or to increase the structural performance).

The implementation of scissor structures dates to the Renaissance when Leonardo da Vinci depicted a flat, deployable structure comprised of these elements [9]. However, it wasn't until Emilio Perez Piñero's traveling theater design in 1961 that modern interest in these elements began [10]. In more recent years, Felix Escrig became one of the main contributors to the field [11]. Hoberman [12] introduced a new concept in the field of scissor structures: angulated elements, which were further generalized by You and Pellegrino [13]. While there is significant literature on and implementation in practice of scissor structures by leading architects and engineers, the novelty of this research is its holistic approach to the design of scissor structures including conceptual design using a parametric finite element (FE) method, experimental validation on a full-scale prototype leading to calibration of FE models, evaluation of support and stiffening methods, and final design according to the European Standards (Eurocodes).

The research presented here focuses on the first emergency phase with a rapidly deployable scissor shelter. Future work will include elaborating on the transitional concept, including reconfiguration for rehabilitation and reconstruction in the development process. This paper will first present the conceptual design approach using a parametric FE tool, including a parametric study leading to design choices. The resulting FE model is experimentally validated and calibrated based on results from experimental testing on the full-scale prototype using Digital Image Correlation and Tracking. Further experimental testing is performed to demonstrate the deployment process, evaluate two methods of support conditions, and test the effect of employing cables to stiffen the structure. This investigation culminates in a final proposed design that meets the requirements of the Eurocodes [14,15]. This research represents a benchmark study, validating a FE model with experimental results and provides valuable insight into the effect of design decisions on the structural behavior of scissor structures. It represents a design solution process including the initial planning and design, construction process, and highlights potential for dismantling and repurposing as a transitional shelter.

2. Conceptual design and analysis

As a preliminary investigation, this research focuses on a deployable scissor structure comprised of three arches and a membrane (Fig. 4).

2.1. Concept: deployable arch structure comprised of scissor elements

The proposed barrel arch concept consists of three aluminum scissor arches (6 m span, height-to-span ratio of 0.5) covered by a fabric membrane (Fig. 4). Each arch is comprised of polar SLEs, meaning SLEs which are connected at points offset from their midpoint to generate a curved shape in the deployed form (Fig. 3(b)). The arches are connected laterally by translational SLEs, meaning SLEs which are hinged at their midpoint by a pin connection to create a linear motion (Fig. 3(a)). In this way, the scissor system deploys from a compact package both transversely (in a curved motion in the direction of the span) and longitudinally (in a linear motion perpendicular to the direction of the span) resulting in a barrel vault-like shelter when fully deployed (Fig. 4). This barrel vault form allows a floor space with a high percentage of usable area. Also, the barrel vault could be expanded indefinitely, to form any desired length, by adding arches along the longitudinal direction to increase capacity and variety of uses. This dimensional flexibility and modularity, together with the uniformity and simple scheme of the basic components (translational and polar scissors), allows the use of the same design process for variant geometries [16]. Moreover, it simplifies the manufacturing, assembly, transportation and storage, which makes it ideal for a transitional shelter system.

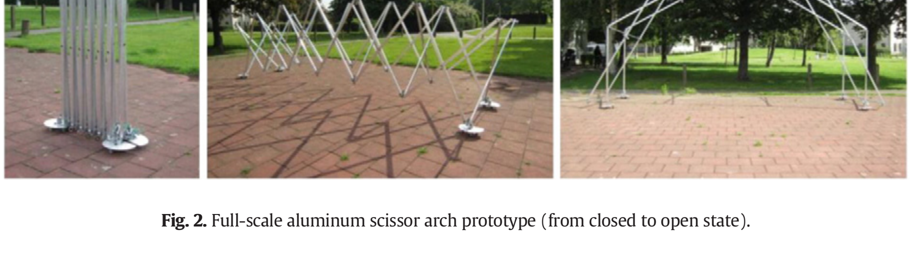

Fig. 2. Full-scale aluminum scissor arch prototype (from closed to open state).