# Component reuse for disaster sheltering: from deployable scissor structures to kit-of-parts structures

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## Abstract

In the aftermath of disasters, many people's homes have been damaged or destroyed and others have been displaced. It is in such tragic moments that humanitarian organizations have an important task by providing shelter assistance for the affected population. Besides the family shelters that are provided for temporary housing, collective service tents are also necessary for field hospital, community centre, food, .... Although the current family shelters are adequate enough for the emergency use, there is a demand for better collective service tents because (i) the current tents are structurally complex which slows the building process, (ii) the current tents are not adaptable, (iii) after the initial emergency phase, these tents are not reused.

The aim of this paper is to investigate a better alternative for collective service tents by using deployable constructions for the first emergency phase after a disaster, and by designing the component as such that they can be reused for a kit-of-part structure for the second phase of the disaster, i.e. the transitional phase.

A first preliminary study is presented in this paper where the structural feasibility of the concept is tested. A barrel vault structure of 6m span and a height of 3m composed of scissor elements is modelled in a finite element program. The structure is then designed to fulfil the boundary conditions for the emergency phase. The components of the barrel vault structure are then used to introduce the idea behind the use of some static kit-of-parts structures for the transitional phase.

The results are very promising. Together with experts from the field, we are very optimistic about the use of deployable shelters for humanitarian relief in order to

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propose a construction which can be used for the emergency and transitional phase of disaster relief.

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# 1 Introduction

## 1.1 An introduction to shelter assistance

The escalating amount of disasters presents huge challenges for humanitarian and development organisations. The most recent data from the Centre for Research on the Epidemiology of Disaster (CRED) mentions 357 natural disasters in 2012. Those disasters have killed 9.655 people worldwide, made 122,9 million victims and caused a record amount of $157,3 billion of damages [1]. Natural disasters are however not the only disasters that affect people. The so-called 'man-made' disasters such as persecution, conflict, generalized violence and human rights violations, affect a lot of people too. By the end of 2012, 45,2 million people were forcibly displaced worldwide as a result of 'man-made' disasters [2].This increase of affected people worldwide, and most of the times in developing countries, is truly alarming.

In the aftermath of disaster, many people's homes have been damaged or destroyed and others have been displaced. It is in such tragic moments that humanitarian organizations have an important task by providing shelter assistance for the affected population, which is off course, a basic human need. When looking at the different responses over the years, an important evolution has been noticed. During the Sphere drafting process in the nineties, the shelter-sector began with sector-specific vocabulary and the introduction of the concept of a 'shelter process' with transitional phases.

Seven different phases of operation can be distinguished [3], the three most important phases being phase 4 until 6: The **emergency phase** can be described as the period during which significant numbers of people are being displaced. The **care and maintenance phase**, which is commonly called the *transitional phase*, is the period between the emergency phase where a significant amount of people are displaced and the point when every member of the displaced population has reached a durable solution and is no longer displaced. At last, the **durable solutions phase** is the period when the displacement has ended because sustainable and permanent settlement and shelter have been achieved for the displaced population.

For each of those phases, different constructions are possible in function of the goal. The International Federation of Red Cross and Red Crescent Societies has published an online catalogue with all the different emergency items that are used nowadays [4]. In this catalogue, the different used constructions are also listed.

For the **emergency phase**, different structures can be used in function of the goal. The emergency shelters are used for the sheltering of affected households. During this emergency phase, there is also a need for larger constructions which are necessary for the *community*, for example for a warehouse, a dispensary, ... Those construction are called *collective service tents*.

For the **care and maintenance phase**, the commonly used constructions are transitional shelters, which are used to allow time for sustainable reconstruction following a conflict or natural disaster [5]. The shelters can have the ability of being adaptable but the most important property of those shelters is that they must fit their purpose. This means that they must be structurally sound, and provide protection from the environment (monsoon rains, cyclones, high temperatures, floods, etc.). A minimum safety for the occupants must also be ensured [6].

### 1.2 Where the shortcomings are and what do we propose

There exist - on the field - an important weakness when looking at the proposed solutions for the emergency phase and the care and maintenance phase. The *emergency shelters* are light, fast to build and are thus adequate for their purpose. There is however a demand for better *collective service tent* because:

– the current tents are structurally complex which slows the building process and causes errors in the construction
– the current tents are not adaptable. Every disaster is different, but the current tents are sold as a 'one size fit all' product with a very limited range of choice
– after the initial emergency phase, these tents are not reused.

The aim of our research is to use deployable structures as alternative to the current kit-of-part collective service tents. What are deployable structures? Structures which are able to alter themselves from a compact configuration to a larger deployed configuration and vice versa [7]. The advantages of deployable structures are the facile transportability, the ease and speed of erection and folding, as well as the high volume difference between compact and deployed state [8]. Deployable structures can be categorized in four main classes in function of their structural system [8]:

– Scissor structures, composed out of beams connected together with hinges
– Foldable plate structures consisting of hinged plates
– Membrane structures
– Tensegrity structures

Because the aim of our research is to use the same structural elements of the deployable structure as kit-of-part structures for the local population during the care and maintenance phase, we want to use a type of deployable structure which can be disassembled easily and where the elements can be combined to a building kit. We are therefore using scissor structures. Scissor units, panthographs [9] or scissor-like elements (SLEs) [10] are structural elements, composed of two straight beams, connected through an intermediate point (a pivotal connection) which enables a single axis rotation in the plane of the structural element (with restriction of all other DOFs) [11]. By hinging scissor units at their end points to each other, a two-dimensional transformable linkage is formed. These structures can be deployed from a compact bundle of SLEs to a fully developed configuration in order to, after adding constraints to the mechanism, achieve a load bearing

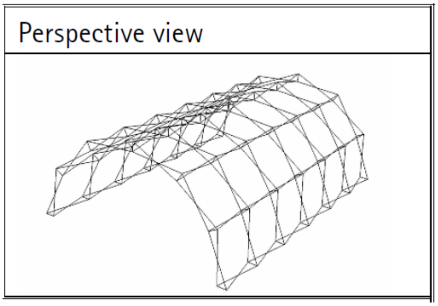


Figure 1: Polar and translational units on a two-way grid [8].

structure [12]. By modifying the shape of the beams and the location of the pivotal connection, we can obtain different units, the most important units for our research being the translational units and polar units.

Our research is focussing therefore on the design, the analyse and the optimisation of scissor structures which can be used as collective service tent for the emergency phase and which can disassembled into his components and used in a building kit to generate different configurations of transitional shelters for the care and maintenance phase. We are quite confident that this solution is a sustainable solution and avoids the shortcomings of current solutions. Our solution can also help the local population to recover faster and build resilience.

In this paper, a first preliminary structural design of a barrel vault scissor structure which fulfils the necessary boundary conditions is presented. The aim is to find an optimal typology for a given span of 6m, and to test the structural feasibility of the concept. The idea behind the use of the same element to design a kit-of-part system is also shorty introduced.

## 2 Conceptual design of the barrel vault

The focus of this paper being a preliminary design of a scissor structure for emergency relief, we have chosen to work with a single curvature two-way grid structure with polar and translational units. The latter can be translated as a barrel vault structure as shown in Figure 1.

In the different paragraphs that will follow, the geometrical and structural parameters of the designed barrel vault structure will be discussed.

### 2.1 Geometrical parameters

It has been chosen to work with polar scissor units for the arches and transitional units between the arches as shown in Figure 1. In order to maximise the compatibility between the barrel vault and the kit-of-part, the same member's length has been chosen for both the polar as translational units. The distance between two arches is therefore fully determined by the length of one translational units and the deployability constraint $a + b = c + d$ which states that in order a structure to be deployable, the sum of the semi-lengths a and b of a scissor unit has to equal the sum of the semi-lengths c and d of the adjoining unit [8].

After some discussions that we had with Y. Garbusinski from Médecins Sans Frontières Operation Centre Brussels Logistic department, it has been noted that collective service tents with an opening varying from 6 to 8 meters are really optimal. In this paper, an **span of 6m** has therefore been chosen.

The **depth** of the barrel vault structure does not matter for this part of the research. In function of the needed depth, different modules consisting of arches and translational units in-between can be added. The preliminary design presented in this paper is analysed using two arches and one set of translational units to link them.

For the **cross-section** of the scissor units, a box with a thickness of 2mm is used. The height *h* and width *b* of the section are determined when carrying the structural analysis.

The **number of units** has directly an impact on the length of the scissor units. The more units, the smaller the elements. Because the aim is to obtain a structure which can easily be disassembled , we have putted a restriction for the length of the elements to 2.5m. This gives us a choice between 4, 6 or 8 units (more than 8 units are not optimal because of the additional weight of the structural elements and the joints between the units).

At last, the **structural thickness** of the barrel vault is chosen to 45cm.

## 2.2 Material

The material that will be used is Aluminium 6061-TG ($E = 69GPa, f_y = 241MPa$), because of his low density in comparison to steel but still with a high strength.

## 2.3 Supports

The barrel vault structure is hinged on each support with the ground, this means on 4 points per arches. In the finite element model of this work, there are therefore 8 supports (Figure 2).

## 2.4 Loading parameters

When determining the load cases and load combination on the barrel vault, the structure has not been considered as a ’temporary structure’. It is indeed unclear during humanitarian crisis how long the collective service tents are used and therefore, it has been chosen to design them as permanent structures. However, the conceptual design of the current barrel vault structure does not take tornadoes, hurricanes or typhoons into account. For readers interested in calculation methods which take the later into account, we refer to [13].

### 2.4.1 Load cases

The first considered load case is the **self weight**.

The calculation for the **force caused by the wind** is described in *Eurocode 1-4: Wind actions* where the barrel vault has to be divided into 3 parts A, B and C as mentioned in Figure 7.11 of the Eurocode [14]. The wind direction is towards the centre of the barrel vault. For the wind speed, the Transitional Shelter Standards written by the Shelter Centre has been used [15]. The wind speed is 18m/s. The values obtained for this research are: $0.48kN/m^2$ (for zone A), $-0.62kN/m^2$ (for zone B), $-0.26kN/m^2$ (for zone C).

The details for the calculation of the **snow loads** are available in *Eurocode 1-3: Snow loads* [14]. Again, for the snow loads, the Transitional Shelter Standards mentions $0,3kN/m^2$ [15].

### 2.4.2 Load combinations

In this work, three load cases are considered: the self weigh *G*, the wind loads $Q_w$ and the snow loads $Q_s$. With the right combination keys as mentioned in [14], different load combinations are obtained as shown in Table 1 and 2.

The first four combinations are used for the strength and stability check in ULS (Table 1); the last 4 combinations are used for the deformation check in SLS (Table 2). Combination 7 and 8 are special combinations where the impact of the wind or the snow without their influence on each other is tested. Because of the small value of the snow loads, combination 8 will certainly not be determinative but combination 7 could be interesting for the deformation, because the snow loads could have a favourable effect on the structure when wind is blowing.

Table 1: Summary of the load combinations for ULS used in this research.

| **Nr** | **Combination** | | | | | |
|---|---|---|---|---|---|---|
| | G | $\Psi_w$ | $Q_w$ | $\Psi_s$ | $Q_s$ | |
| 1 | 1.35 | 1 | 1.5 | 0.6 | 1.5 | $1.35 \times G + 1.5 \times Q_w + 0.9 \times Q_s$ |
| 2 | 1.35 | 0.6 | 1.5 | 1 | 1.5 | $1.35 \times G + 0.9 \times Q_w + 1.5 \times Q_s$ |
| 3 | 1.35 | 0 | 1.5 | 1 | 1.5 | $1.35 \times G + 1.5 \times Q_s$ |
| 4 | 1.35 | 1 | 1.5 | 0 | 1.5 | $1.35 \times G + 1.5 \times Q_w$ |

## 2.5 Properties of the finite element model

For this model, B31-elements are used in Abaqus (Beam, 3-D, 1st-order interpolation), and the convergence has been obtained after reducing the mesh size to 2,5mm.

Table 2: Summary of the load combinations for SLS used in this research.

| Nr | Combination | | | | | |
|---|---|---|---|---|---|---|
| | G | $\Psi_w$ | $Q_w$ | $\Psi_s$ | $Q_s$ | |
| 5 | 1 | 1 | 1 | 0.6 | 1 | $1 \times G + 1 \times Q_w + 0.6 \times Q_s$ |
| 6 | 1 | 0.6 | 1 | 1 | 1 | $1 \times G + 0.6 \times Q_w + 1 \times Q_s$ |
| 7 | 1 | 1 | 1 | 0 | 1 | $1 \times G + 1 \times Q_w$ |
| 8 | 1 | 0 | 1 | 1 | 1 | $1 \times G + 1 \times Q_s$ |

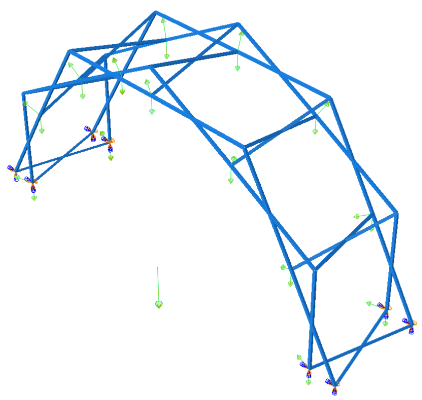

Figure 2: The finite element model presented in this paper for 8 units.

In order to simulate the effect of the intermediate node, the legs have been defined as parts (one leg = one part) with a Join + Revolute (hinge) connector in-between, each time perpendicular to the part's local axis. Because the membrane has not been modelled in this work, the wind and snow loads acting in fact on the membranes have been simulated as point forces on the different nodes (the green arrows in Figure 2). The vertical downwards green arrows on the nodes stands for the snow loads, the radial green arrows for the wind loads and the big green arrow for the self weight. One can note that the radial arrows are sometimes directed towards the inside of the barrel vault, and sometimes away from it. This is because of the pressure/suction effect caused by wind (in the example of Figure 2, the wind is blowing from right to left and this causes pressure on the right side (zone A) and suction on the upper and left side of the dome (zone B and C).

# 3 Structural analysis on the barrel vault

After making a convergence analysis of the finite element model, the elements of the barrel vault structure have been dimensioned in function of the forces acting on the structure. Different analyses have been realised in order to calculate the maximum stress, the maximum deformation and the critical eigenvalues.

## 3.1 Results and discussion of the analysis

The first step is to analyse the most critical load cases for the calculation of the stress, the eigenvalues, and the displacement (Table 3). Then, the following parameters are calculated in function of the span for the most critical load cases (Table 4):

- $n_{units,pol}$ - Number of polar units per arches
- $l_{leg}$ - Length of the scissor element: this is the length of one leg of the scissor element
- $A_c$ - Optimal cross-section: this is the cross-section needed in order to fulfil the strength criteria and local buckling (height x width).
- $V$ - Volume: this is the volume of the structural elements made of Aluminium of the barrel vault structure
- $\delta$ - Deformation: this is the maximal deformation of the structure under SLS
- $\sigma_{max}$ - Maximal stress: The maximal stress in the whole structure under ULS (must be lower than 241MPa)
- $\lambda$ - Eigenvalues: If this value is greater than one, global buckling doesn't occur (ULS).

Table 3: Comparison between the different load cases for 6 units and a cross-section of 40x25mm.

| LC | $\delta$ (cm) | $\sigma_{max}$ (MPa) | $\lambda$ |
|---|---|---|---|
| **1** | | **234** | **-1,807** |
| 2 | | 114 | -2,4857 |
| 3 | | 795 | 3,6433 |
| 4 | | 231 | -1,9301 |
| 5 | 7,37 | | |
| 6 | 5,63 | | |
| **7** | **7,46** | | |
| 8 | 1,56 | | |

Table 3 gives a good overview of the impact of the different load cases. The results are in fact what we expected. Because the biggest load case is the one produced by the wind, for the strength criteria but also for the eigenvalue, the load case with the highest safety factor on the wind will be decisive. This is load case 1. For the deformation, as expected too, load case 7 is decisive. The snow is favourable for the structure when the wind is blowing. Therefore, when the snow is not considered, the biggest deformation is obtained.

Table 4: Comparison between barrel vaults with different number of units.

| $n_{units,pol}$ | $l_{leg}$ (m) | $A_c$ (mm$^2$) | $V$ (cm$^3$) | $\delta$ (cm) | $\sigma_{max}$ (MPa) | $\lambda$ |
|---|---|---|---|---|---|---|
| 4 | 2.50 | 55x45 | 12740 | 11 | 235 | -2.35 |
| 6 | 1.72 | 40x25 | 8259 | 7 | 234 | -1.81 |
| 8 | 1.34 | 45x35 | 10452 | 6 | 217 | -5.82 |

Different important conclusions can be made from the performed analysis (important results shown in Table 4). As it can be seen, the optimal number of units is 6. One can notice that the length of the scissor units becomes smaller for increasing number of units (for the same span of 6m) which is of course trivial. For a number of units of 4, the length of the unit is 2.5m, which is the upper limit set in the previous section.

As shown in Table 4, the number of units is not inversely proportional to the needed area for the cross-sections of the scissor units. When going from 6 to 8 units, the additional weight becomes too important and the stresses in the elements are higher. This difference in weight is not so important when going from 4 units to 6 units. There is therefore an optimum number of units in function of the span and the loading conditions. In this case, this optimum is 6 units.

Figure 3 shows the distribution of the stress in the finite element model for the same wind distribution as Figure 2. In this same figure, the maximum deformation of 7cm is shown. This figure gives a good idea of the deformation that the structure will have to endure under load case 7 for 6 units.

## 4 A short introduction to the concept of kit-of-parts structures

In this section, only the concept behind the idea will be explained.

Taking into consideration the barrel vault structure with 6 units, one can note that the same leg is always used. The leg is 1.72m long and has a cross-section of $(40x25)mm^2$. The aim now is to disassemble the barrel vault structure and to use the cross-section to design truss sheds. The truss shed must therefore have members who are multiples of 1.72. In the sketch shown in Figure 4, an example

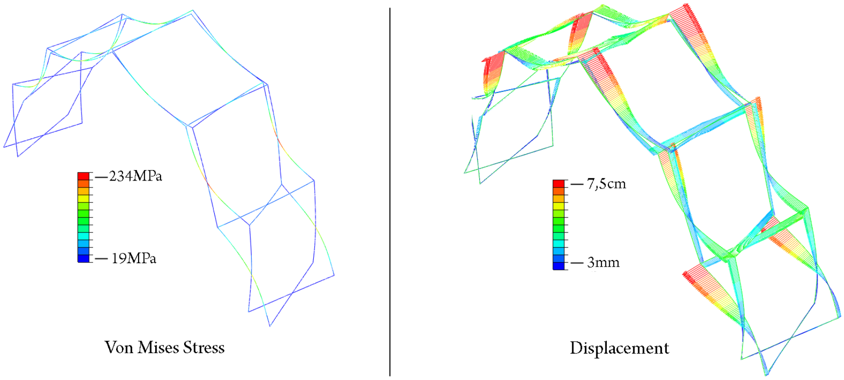


Figure 3: The stress distribution and the displacement vector of the barrel vault structure with 6 units under load case 1 (for stress) and 7 (for displacement).

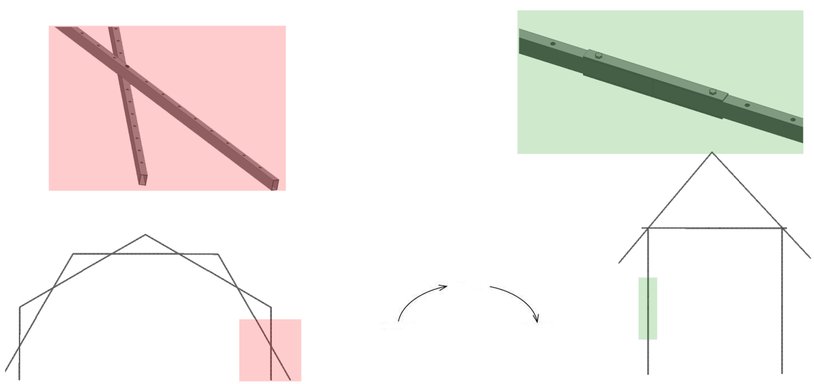

Figure 4: An example of the process from deployable shelter to transitional shelter.

of the process is given. After a structural analysis on those structures, we could give an overview of the needed elements for different kind of shelters.

Because the structural element of the scissor structure needs to be used for different purposes, they have to allow adaptability. Therefore, the proposition is to procure, before the construction of the barrel vault, in each element, different holes for bolts as shown in Figure 4. By opting for this, the same structural element can be used for different purposes.

## 5 Conclusion and further work

Because of the lack of compatibility between the collective service tents used for the emergency phase and the transitional shelters for the care and maintenance phase, our research is focussing on the design, the analyse and the optimisation of scissor structures which can be used as collective service tent for the emergency phase and which can disassembled into his components and used in a building kit to generate different configuration of transitional shelters for the care and maintenance phase.

A first preliminary study has been presented in this paper where the structural feasibility of the concept is tested (the focus laid on the barrel vault structure). It has been seen that 6 is the optimal number of units per arches for the boundary conditions of this work and a span of 6m. The optimal cross-section is $(40x25)mm^2$. Furthermore, the pressure and suction effect of the wind had a great important on the deformation of the structure.

At last, a very brief introduction has been formulated to make the link between the scissor arches and the kit-of-part structure.

The results of this paper are very promising because it shows the structural feasibility of the concept. Our research will now focus on a better optimisation of the structure, not only to the weight, but also to the compactness. In order to optimise those structures, multi-criteria optimisation algorithms will be used. Furthermore, the kit-of-part solutions will be elaborated, a structural analysis will be realised for the different concepts and finally, the building kit will be designed.

## References

[1] Guha-Sapir, D., Hoyois, P. & Below, R., *Annual Disaster Statistical Review 2012: The Numbers and Rends*. CRED: Brussels, 2013.

[2] Office of the United Nations High Commissioner for Refugees, *Displacement, The New 21st Century Challenge. Global Trends 2012*. United Nations High Commissioner for Refugees: Geneva, Switzerland, 2013.

[3] Corsellis, T. & Vitale, A., *Transitional settlement displaced population*. Oxfam GB: Oxford, 2005.

[4] International Federation of Red Cross and Red Crescent Societies, Emergency items catalogue, 2014.

[5] Centre, S., *Transitional shelter guidelines*. Shelter Centre, 2011.

[6] Silva, J.D., Transitional shelter quality, standards and upgrading guidelines. *UNHCR*, 2005.

[7] Jensen, F.V., *Concepts for rectrable roof structures*. University of Cambridge, 2004. PhD Dissertation.

[8] Temmerman, N.D., *Design and Analysis of Deployable Bar Structures for Mobile Architectural Applications*. Vrije Universiteit Brussel, 2007. PhD Dissertation.

[9] Pinero, E.P., *Project for a Mobile Theatre – Architectural Design*. Volume 12 edition, 1961.

[10] Gante, C., *Deployable structures: Analysis and Design*. WIT Press, 2001.
[11] Akgü, Y., *A Novel Transformation Model for Deployable Scissor-Hinge Structures*. University of Stuttgart, 2010. PhD Dissertation.
[12] Alegria Mira, L., *Design and Analysis of a Universal Scissor Component for Mobile Architectural Applications*. Vrije Universiteit Brussel, 2010. Master thesis.
[13] Federal Emergency Management Agency, *Design and Construction Guidance for Community Shelters*. FEMA, first edit edition, p. 222, 2000.
[14] Eurocode 1, *Eurocode 1: Actions on structures*. CEN Central Secretariat, 2002.
[15] Shelter Centre, *Transitional Shelter Standards (draft)*. Shelter Centre, p. 29, 2010.