Back to the Future
Reverse-designing a shelter for extreme weather in Antarctica

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ABSTRACT: The impacts of climate change and extreme weather events can be seen all around us, causing record-breaking damage. Such events, coupled with wars and social unrest, are resulting in people losing their homes at an unprecedented and growing rate, forcing them to rely on semi-permanent structures. To explore the design of these structures in extreme cold, a prototype tent made of innovative materials, capable of resisting the extreme weather in Antarctica, was made, and tested, on a site at King George Island, in 2019. The shelter was left on-site there for twelve months, during which some damage was recorded, resulting in high levels of humidity in the structure, and wind damage on the outermost fabric layer. This paper attempts to reverse-design the tent comparing theoretical, and field data. Using an algorithmic design tool, the shelter was modelled within the site contours, and comfort and airflow simulations were made to assess the thermal properties of the used materials. Durability and comfort performance are discussed and compared with permanent standard structures, as are their implications on the design of similar projects in extreme weather conditions in future unpredictable climates.

KEYWORDS: Extreme Design, Comfort, Algorithmic Design, Building performance simulation.

1. INTRODUCTION

Over the past decades, disaster-related events have been responsible for the displacement of millions of people around the world, and roughly 90% of those are weather-related [1]. Buildings are increasingly failing because of the escalating impacts of climate trends and weather events [2]. Moreover, it is estimated that by 2050 there will be an increase from 55% to 68% of the world population living in urban areas, and most of this urbanization will have to be prepared for a very different climate and environment [3]. A recent study on coastal flooding indicates that up to one billion people now occupy land which is less than 10 meters above current high tide lines, including 230 million below 1 meter, and these numbers will increase as people flock to coastal cities [4]. With the consequent explosion in health emergencies and social, economic, and climate issues, people will require huge numbers of adaptable temporary structures. With that in mind, a multidisciplinary team was assembled to develop and experiment with a yurt-like tent in Antarctica, to take lessons from the extreme weather, to improve and adapt temporary shelters in the field, and to prepare them against future weather conditions.

Four expeditions to King George Island resulted in the development of a high-performance shelter at Collins glacier (Fig. 1), which can be easily built in a day and house up to four field workers comfortably while resisting extreme winds and cold temperatures throughout the year. A prototype inspired on a traditional Yurt was mounted in Antarctica in 2016 (PL1) [5], but it proved to have some shortcomings in terms of thermal performance, and its structure collapsed during a storm with wind gusts of over 170kmh.

The design was then improved, after exploring new solutions to increase structural resilience, make it more wind resistant, and using innovative materials to improve thermal performance and water tightness. A novel skin envelope was finally chosen, composed of two skins of a new lightweight, eight-layer material called ORV8, one in each side of the timber structure, surmounted by an outer layer of Dyneema made of recycled racing yacht sails. ORV8 underwent preliminary testing in a cold facility in the UK and proved very effective as a thermal insulator [6]. The second tent (PL2) was constructed in England, incorporating these materials, and then transported for testing on-site at Collins Bay, Antarctica, in 2019, where it was easily erected, tested, and reported on, for its siting [7] and its structural [8] and thermal [9] performance. A key finding of that experiment was that the inclusion of theoretical assumptions should be backed up by liaising with experts, bench and field testing, and simulation to validate performance analyses and optimize the design [10].

What proved difficult in testing the new materials was their property characterization. Dyneema is one of the strongest materials, given its weight and strong resistance to wind and rain, making it ideal for high-performance racing sails [11]. The two multi-purpose layers of ORV8 had not been tested before the PL2 team's experiment, which was conducted in a cold room with one person occupying the tent for 15 minutes. The indoor heat gains were of 1.1ºC per minute, ranging from -15 to -5 ºC, and tripled when a small gas heater was deployed. Even though these tests lacked more robust information on the materials' thermal properties, it was decided that the final tent would be built for field testing.

Fig. 1 - Polar lodge drone view at Collins glacier.

In February 2020, a third field trip to Collins Bay was undertaken to see how the tent withstood the extreme weather conditions in the twelve previous months. Upon arrival at the site, the tent looked intact. The structure resisted the 2019 Antarctica Winter without any damage. In terms of its envelope, a detailed damage report showed that it had suffered slight deterioration, including small rips on the external Dyneema layer, damp accumulated between the lower and upper groundsheets, and moisture damage on some of the tent wall trellis members and rafters. The location and intensity of the damage were mapped and recorded in a full condition report for the tent after its first year.

After reviewing the gathered data, several questions emerged regarding the causes of envelope damage, and the thermal properties of the innovative materials. These are important to understand the long-term potential of this shelter as a semi-permanent structure rather than as a temporary, seasonal one. This was particularly relevant for the head of the Chilean Base, who was interested in using the tent as temporary housing for workers during the summer season. To answer these questions, this research aims to use simulation, informed by readings taken on-site, to reverse-engineer the shelter to better understand its future usefulness as a shelter in the local climatic conditions and geomorphological context.

The adopted methodology integrates Algorithmic Design (AD) and Building Performance Simulation (BPS) after the design and construction process, as opposed to traditional applications of AD and BPS which are made, respectively, during early and final design stages. The goal is to (1) provide a better understanding of the damages reported in the envelope material properties, (2) correlate the comfort metrics gathered in the field with the simulation results, and (3) compare the shelter's performance against a permanent heavyweight structure within the same climatic conditions.

2. WORKFLOW

To achieve the proposed goals, the workflow presented in Fig. 2 starts by analyzing the data collected from an expedition to Antarctica, particularly, regarding the damage suffered by the envelope shelter, and moves on to the use of an algorithmic design and analysis tool to model the shelter and simulate its behaviour [12]. One of the advantages of this tool is its ability to coordinate different analyses, as well as integrate them with optimization algorithms within the same platform [13].

The design is parametric, to facilitate the rapid adjustment of design parameters during the analysis and comparison stage. Executed analyses in this research comprise CFD (Computer Fluid dynamics) and comfort simulations, which will respectively provide metrics such as wind velocity, and direction, around the structure, and indoor comfort metrics.

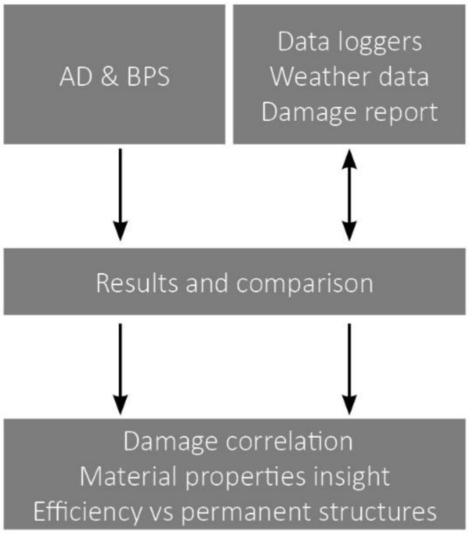

Fig. 2 – Research workflow.

2.1. Damage, weather, and indoor comfort metrics

Weather data was retrieved from the local Airport Operations Center and contains a CSV file with wind speed (kt), and direction from March 2019 to February 2020, thus allowing the simulation of extreme scenarios to which the shelter was exposed during the Antarctic winter.

The initial visit to the shelter's site on the third field trip there was made to assess its condition and damage, which showed that the outdoor window was partially open over winter, and there were some shreds in the Dyneema layer (Fig.3). These were mapped and incorporated in a model for further correlation with wind speed data. The hypothesis is that the wind speed was sufficient to create the Von Kármán Vortex Street pattern responsible for generating fabric vibrations, which ripped in its seams [14]. Through the CFD simulation, it is possible to check if high speeds are occurring in the shredded areas, indicating the creation of these patterns and the necessity of applying a different method to attach the envelope layer. Following the damage survey, data loggers were implemented outdoors and indoors during the whole mission period, collecting temperature, relative humidity, and illuminance.

Fig. 3 - Temporary mend of the envelope shreds with tape and safety pins

2.2 Algorithmic design and analyses

The parametric model was created with an AD tool, using a simple BIM space syntax. Parameters used that may vary are the trellis bottom and top radius, number of beams, trellis and roof height, width and length of the beam section, and the interval in which the beams connected each other from bottom to top. In this case, the height of the trellis was 1.5m and 1.2m for the beam length (Fig.4). Furthermore, the model is automatically exported in the required geometric format for each simulation.

OpenFoam© was used to simulate outdoor airflow using, as input parameters, wind speed and direction, test geometry, and the simulation area. We tested the most extreme case in each month since last year's expedition. August, for example, brought winds over 30 knots that came mostly from East and Southeast, and the highest recorded speed was 70 knots from the East. The output of the simulation is the wind speed and direction in all tested points within the test area.

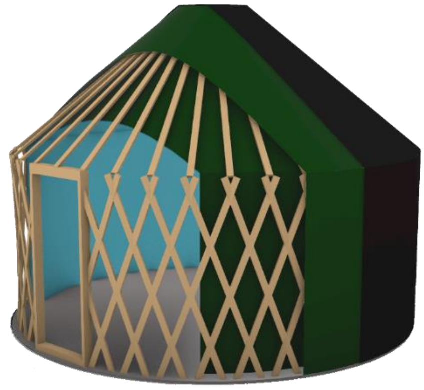

Fig. 4 - Parametric model section – showing in green the inner layer of ORV8, Trellis, and the outer layer of ORV8 and black Dyneema sheet cover.

The inputs of the comfort analysis encompass (1) the shelter geometry; (2) the material properties, namely thermal conductivity, density, specific heat, thickness, and absorptance; (3) weather file, namely relative humidity, dry bulb temperature, and dew point temperature values gathered in the site during the expedition period; and (4) schedules describing occupancy, equipment, lighting, cooling, and heating. The equipment was switched off during the unoccupied periods and were used only during the two nights spent in the shelter for repairs, surveys, and field testing.

Material properties were developed from largely referenced values, except the ORV8, which is composed of *orve+wrap©*, with an additional internal lining of fleece and polyurethane on the outer layer[i]. Laboratory test results were available for *orve+wrap©* that revealed its thermal resistance, emissivity, dimensions of sample, heat flux, and temperature difference for both cold and hot surfaces. This is enough to deduce the conductivity, density, specific heat, and material absorptance. The final values applied in the simulation can be seen in table 1.

Simulation outputs were compared with the data loggers regarding indoor operative temperature and relative humidity. Subsequently, a correlation was

Table 1 – Material properties used for the simulations

	OrveWrap	Fleece	PU	Wood	Dyneema
Thickness (m)	0.0051	0.001	0.001	0.01	0.001
Conductivity (W/m-K)	0.033	0.15	0.03	0.11	20
Density (kg/m3)	0.5776	23	32	510	980
Specific heat (j/kg-K)	2800	1350	1800	2301	1850
Absorptance	0.48	0.9	0.95	0.9	0.9

made and used to quantify maximum and minimum temperature deviation values between field and simulation results and compared with the elaborated damage report.

3. RESULTS AND DISCUSSION

From the proposed workflow, the following sections follow a categorized approach in which results and discussion are divided into two stages that consider the proposed objectives, which are:

- Damage assessment and prevention.
- The relevance of AD and BPS for the design for extreme conditions.

In the first stage, a damage report is compared with simulated wind tunnel tests, and from observed air circulation, it might be possible to check if any correlation exists between the simulations and the shredded fabric. The second stage will show the operative temperature in the simulated parametric model and its comparison with the recorded indoor values during the field expedition period. Additionally, the Lodge's performance will be tested against one of a permanent standard structure for the same weather.

3.1 Damage report and airflow simulation

The Venturi effect is well-known in fluid dynamics: when a fluid flows through a constricted section, its velocity increases and its pressure diminishes [18]. This also occurs on a macro scale, throughout urban and natural areas due to topography and the built environment. The lodge was deployed in Collins bay between the refuge base and a rocky slope, which creates constricted sections and makes it prone to higher wind speeds in these areas. Dyneema rips were numbered and mapped through their position and height to include them in a model of the shelter at Collins bay area. These were found on the structure's eastern, western and northern sides, with heights varying from 5 to 80 cm (Fig.5). Additionally, predominant winds were recorded coming from East, West, and North, and respective highest speeds were 70, 44, and 40 knots respectively.

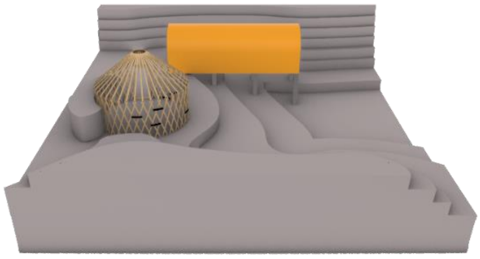

Fig. 5 – Mapped envelope shreds within the site contours.

Three simulated wind tunnel tests with a 45-second duration were made using the three identified predominant directions and a wind speed of 70 knots, hitting the terrain, the shelter, and a recently erected adjacent rock wall. Results from northern and eastern wind analysis showed higher values (≈ 20 knots) in the damaged areas due to the constrictions created by the shelter's cylindrical geometry, the terrain near the eastern side, and the permanent refuge in Collins bay, on the western side. Moreover, the western wind analysis showed high speeds hitting the rock wall area, which prevented vortexes creation. The speed heat and vector maps (Fig.6) show a clear relation of high speeds and constricted areas with damaged zones in the structure. Furthermore, the above-described Venturi effect is observed, and it might arguably indicate the probability of Von Kármán vortex street patterns appearing where the wind speed is higher, which might be responsible for Dyneema fabric rips.

The observed results might explain the appearance and location of the damage and help prevent and protect high-risk structure areas that might suffer damage in the future. Furthermore, it shows the usefulness of these simulations in creating comfortable urban spaces.

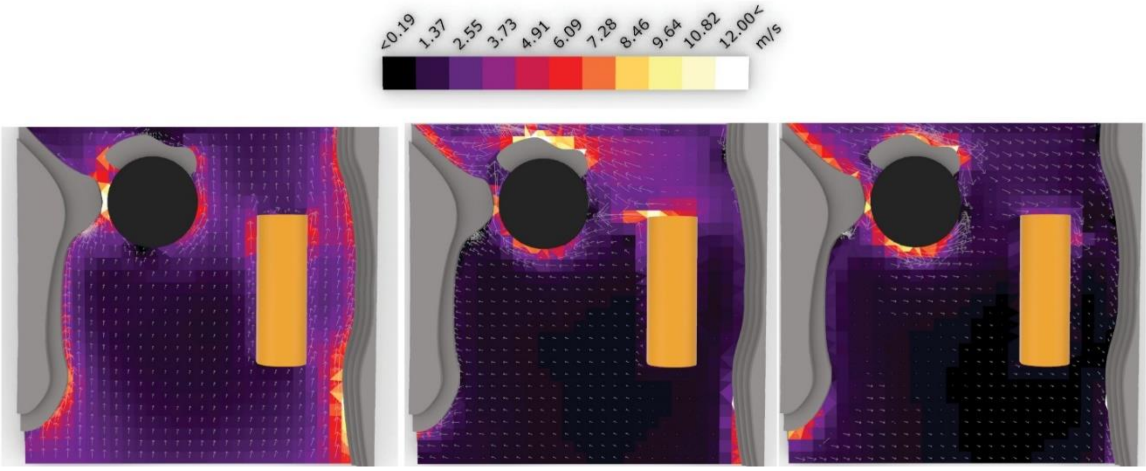

Fig. 6 – Northern, Western and Eastern wind speeds (left to right), and respective velocities visible in a heatmap.

3.2 Comfort simulations

Upon arrival at Collins glacier, loggers were set from February 2nd to 9th, and the team occupied it for repairs and surveys from the 5th in the afternoon to the 8th in the morning, which meant that the door had to be open for most of the repairs, and the gas heater was used in the early night. During this period, simulation results for the shelter's operative indoor temperatures show the biggest discrepancies, since occupancy schedules were turned off. While considering this period, it is visible an average deviation between logged temperatures in the field and those simulated of ± 3 degrees °C, and with maximum values reaching a standard deviation of 10 °C. However, if we exclude the occupied period, this lowers considerably to an average of ±1 °C and a standard of 5.5 °C (Fig.7).

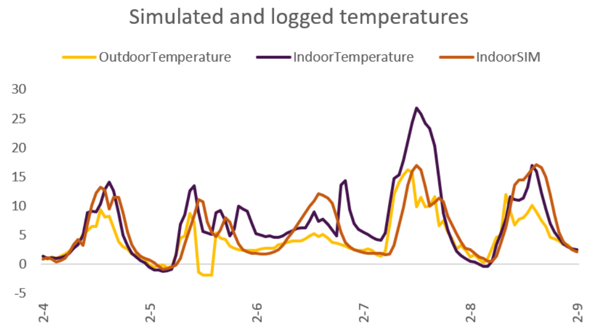

Fig. 7 – Indoor and outdoor operative temperatures logged in the field and simulated indoor temperature

Results show good thermal heat storage during the day regarding the tent performance, with values reaching over 25 °C with a small gas heater turned on, and 15 °C while unoccupied. Nevertheless, minimum temperatures of ≈0 °C, similar to outdoor temperatures, were registered during unoccupied nights around 1:00 AM (Fig.8). Additionally, the high humidity values and the damage registered are an indication that the shelter is not doing well regarding infiltrations, suggesting that additional steps are needed to address this issue. Finally, these results indicate an accurate simulation that allows estimating the tent performance throughout the year, with an acceptable level of confidence.

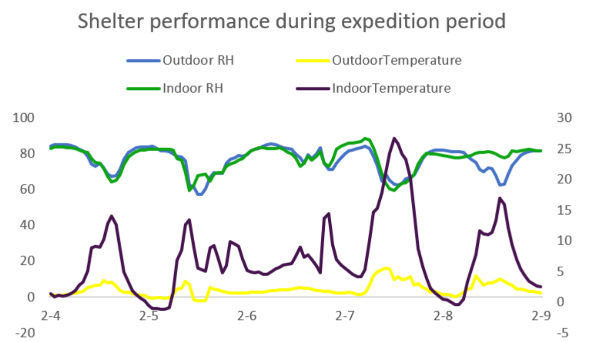

Fig. 8 – logger results for indoors and outdoors relative humidity (left y-axis) and temperature (right y-axis)

When comparing the shelter's annual indoor temperatures with that of a permanent structure with standard grade materials, the latter shows less thermal amplitude. From the heatmap presented (Fig.9), the shelter's temperature reaches averages of 4 °C during the night and 14 °C during the afternoon. However, during hard winter it shows an inability to sustain human life without extra support, with temperatures reaching -14 °C. This is where the standard structure proves itself to be more efficient since it is visible a smaller thermal amplitude with minimum values of -2 °C and maximums of 5 °C during winter. These results confirm that despite the shelter adequacy for summer expeditions, it is still a long way from being able to support life during winter when compared to a heavyweight structure.

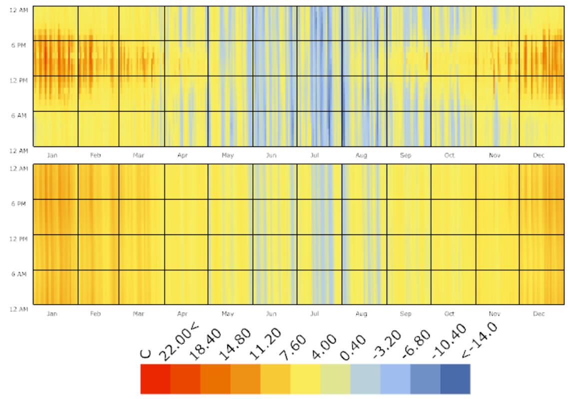

Fig. 9 – Annual Indoor temperatures: Shelter on top and standard structure below. X-axis – months of the year; Y-axis: day period.

4. CONCLUSIONS AND FUTURE WORK

This article started by identifying emerging topics of global development such has home displacement due to weather events, over-urbanization, and future climatic environments. These were addressed through the design, construction, and deployment of a shelter capable of resisting extreme weather, namely, cyclonic winds, and cold temperatures, near Collins Glacier in King George Island, Antarctica. After a year in-situ, a field excursion was organized to survey the condition and repair damages the shelter might have suffered, as well as gather data about the tent performance. The observations raised many questions regarding the reasons behind the envelope damage suffered by the shelter, the properties of the used innovative materials, the reliability of simulation tools in early design stages, and the shelter's performance when compared to structures such as the ones seen in classic Antarctic bases.

Through the integration of Algorithmic Design (AD) and Building Performance Simulation (BPS), a 3D model was created and tested with airflow and energy simulations. A simulated wind tunnel test was compared with the damage location in the outermost layer of the design and gave insights regarding the importance of the geomorphological context of the site and of the deployment and positioning area of the shelter to avoid further damage. Energy simulations returned indoor temperature values similar to the gathered field data with an average error of ±1 ^{0}C for unoccupied periods, proving the reliability of the used simulation tools. Finally, the shelter's annual performance was compared with that of a standard heavyweight structure regarding indoor operative temperature, uncovering issues that need to be addressed, such as the humidity permeability of the shelter, which may be affecting the tent performance during winter. Accordingly, the permanent structure showed better results during this period, indicating that there is still work to be done regarding the design optimization of this shelter for winter use.

This research also identified errors that might be the result of mishandling data loggers, of the occupancy schedules during the expedition, of the material properties and construction layers used for the simulation, and even the simulation tool itself, which cannot be fully validated unless data loggers are deployed in the shelter for the whole year. All these might be affecting readings on-site and yearly simulation values, although results from the short period data sample appear to be compatible with theoretical values, which confirms the usefulness of AD and BPS.

Future work on this topic is going to be conducted around the exploration of design parameters and its integration with structural analysis and optimization, to minimize weight while maximizing portability and performance. This can be done through CFD analysis of wind loads based on the registered wind speed. With the results, it is possible to apply a multi-objective optimization approach to minimize the shelter deformation and minimize its cost according to the material and the respective amount required to withstand such extreme climates. We are convinced that integration of this optimization process can prove helpful in the creation of adaptive solutions capable of responding to the rising challenges from this decade.

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