Is there a case for gridshell structures in humanitarian assistance and disaster relief efforts?

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ABSTRACT: *This article focuses on the core concerns of shelter and settlement, and more specifically focuses on large-span shelters in humanitarian assistance and disaster relief (HA/DR) efforts. Furthermore, this article introduces the audience to novel large-span structures called gridshells. This paper presents a parametric, computational study that quantifies the efficacy of bracing orientation and arrangement on the load carrying capacity of gridshells. The varied parameters include the grid density ("16 by 16" to "30 by 30") and the bracing scheme (unbraced, continuous fully-braced, discontinuous fully-braced, continuous half-braced, and discontinuous half-braced). Four load cases were analyzed, namely a symmetric distributed load, an asymmetric distributed load, a centered point load, and an off-centered point load. The results of the study provide designers with trends and basic design options upon which they can base further analysis depending on the requirements of the final structure.*

KEYWORDS: *Humanitarian assistance, Disaster relief, Shelter, Gridshells, Parametric studies, Bracing, Buckling*

1 INTRODUCTION

Humanitarian assistance and disaster relief (HA/DR) efforts generally comprise three distinct phases following a disaster strike: response, recovery, and restoration (Disaster Response in Asia and the Pacific 2013). The response phase lasts for approximately two weeks following the initial disaster. Throughout this period, search and rescue operations are prevalent and necessities such as food, water, and shelter are points of focus. The recovery phase follows the initial response phase and generally lasts between one and twenty weeks. Hallmarks of the recovery phase include establishing basic local services such as hospitals, housing, sanitation, and more. Robust family shelter construction also begins during this period. Finally, the recovery phase marks the transition from a disaster relief situation to more stable, post-disaster existence. The entire timeline often takes place over many months, though it is common for the recovery phase to last longer. Furthermore, modern crises have a higher likelihood of becoming a protracted crisis, stretching the typical timeline from months to years. Perhaps the most poignant example of a protracted crisis is the global refugee crisis which sees nearly 80 million people displaced (Figures at a Glance 2020). These crises force populations to relocate entirely, often erasing the possibility of a true restoration period, instead resulting in an indefinite state of stifled recovery.

The generic timeline for HA/DR is of course an oversimplification of highly complex and fluid response efforts, yet the outline still serves as an adequate roadmap. The disaster relief timeline indicates that after the initial response period, the recovery period focuses on establishing better small-scale structural solutions for family accommodations, as well as some community services. While vitally important, this focus neglects larger structural solutions aimed at facilitating community gathering. Large-span structures are highly important to city planning because they accommodate and encourage community cohesion. Even in temporary settlements, large-

Figure 1: *ZA Pavilion, fully constructed in Cluj, Romania* (*Photo by Dragos Naicu*)

community cohesion. Even in temporary settlements, large-span shelters are necessary because of the physical space required for religious services, leisure, educational activities, industry and business, and community gatherings. Beyond the physical requirements for space, large-span shelters support community fellowship, an extremely important aspect of mental and emotional health (Project for Public Spaces 2018).

There are no purpose-built, large-span structures currently used for HA/DR. This non-availability is likely due to a lack of understanding of their importance, a focus on establishing other comforts for impacted populations, and a lack of adequate structures to fit this need. Structures such as durable expeditionary tents, shipping container structures, and ready-made deployable structures have characteristics that can make them advantageous for use in HA/DR scenarios, yet when it comes to large-span shelter, each is quite limited (Concrete Canvas Limited 2018, Edilsider 2020, Operator's and Unit Maintenance Manual 1999).

This paper introduces gridshells as a potential solution. Gridshells are a type of shell structure that can be used as a temporary shelter. Gridshells are spatial shells made of an initially flat, structural lattice that is subsequently bent onsite into a doubly curved surface for shelter. Gridshells are most popular in Europe as architectural centrepieces and atrium enclosures, yet their potential stretches beyond these applications. Research indicates that gridshells constructed from long, thin pieces of timber are extremely effective in providing large-span shelter. The ZA Pavilion in Cluj, Romania demonstrated that a self-supporting 12 m by 18 m pavilion could be constructed using only hand tools and a volunteer workforce, see Fig. 1 (Naicu, Harris, & Williams 2014).

When designed with HA/DR in mind, gridshells are highly portable because they require no heavy machinery for construction and can be packaged neatly in standard shipping containers. The structures are also highly sustainable due to their natural construction, modular and replaceable parts, and ability to be assembled and disassembled numerous times. This paper shows that the shells themselves are structurally efficient by design and maintain durability and strength under extreme loading conditions caused not only by wind and precipitation, but also by asymmetric loads such as children climbing on the structure or patrons hanging belongs underneath.

In addition to their many engineering accolades, gridshell structures are inherently beautiful, an attribute often overlooked in HA/DR efforts when the focus is on basic survival. After the initial response period, beauty can become an important factor during the recovery period to facilitate rehabilitation. Humans naturally seek that which is pleasing to the eye, often subconsciously. Providing beauty and balance amidst a crisis, however small, can have large impacts on the mental and emotional health of those affected by trauma.

2 PROBLEM STATEMENT

Completed in 1975, Frei Otto's Mannheim Multihalle was one of the first freestanding large-span gridshells designed as an enclosure for public events (Happold & Liddell 1975). Since then, gridshells have been used as pavilions and atriums in structures such as the British Museum, the Palacio de Comunicaciones, the Dutch Maritime Museum, and others (Sischka 2000, Schlaich et al. 2009, Adriaenssens et al. 2009). During the design of these structures, the primary concern was failure due to global buckling, often the dominant failure mode for gridshells (Knippers & Helbig 2009). Global buckling occurs when an entire structure collapses at once, rather than a single part of the structure experiencing failure. While these structures have been extremely successful, gridshell technology holds the potential for use in the broader built environment beyond these niche applications.

In order to adapt the structures for new applications, additional research must investigate how these structures perform under asymmetric load cases, in a broad sense, and how bracing can improve their structural performance. Symmetric loads are very common in engineering practice, while asymmetric loads are less commonly dealt with when designing gridshells. A symmetric load can be thought of as a balanced load that affects the entire structure in the same manner, while an asymmetric load is unbalanced. Bracing is widely used to stiffen gridshells; however, little research has investigated the extent to which bracing placement and orientation affects structural performance under both symmetric and asymmetric loads (Naicu, Harris, & Williams 2014). This paper aims to establish trends associated with gridshell performance under these circumstances in order to inform design decisions.

3 METHODOLOGY

The research methodology, based on previously employed methods, focuses on developing a viable candidate structure to act as a basis for parametric variations (Malek, Wierzbicki, & Ochsendorf 2014). The results are validated numerically, using an independent finite element analysis (FEA) software, because closed-form analytical solutions are currently impossible to generate and experimental verification was not possible with available resources.

3.1 Design of Candidate Structure

The general features of the candidate structure are fixed, while geometric properties such as grid density and bracing are varied. Grid density refers to the number of grid spaces that comprise the lattice and bracing refers to the elements added to stiffen the lattice. Higher grid densities result in a "finer" lattice mesh pattern.

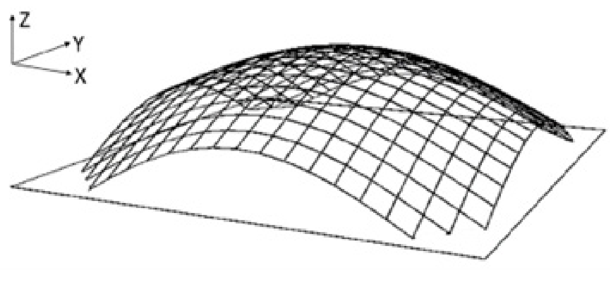

Figure 2: The candidate gridshell structure with a clipped square grid and three distinct touchdown points per corner

The candidate gridshell features a 15 m "clipped-square" grid with four corner supports, see Fig. 2. Each corner support is comprised of three distinct touchdown points per corner, helping to alleviate high compressive forces near the boundaries. High compressive forces near the boundaries cause the wooden beams near these locations to break, leading to structural failure when less than three distinct points are used. The entrance arches on each side (four in total) are fixed at a height of 2 m. The maximum height at the centre of the shell fluctuates due to the geometric variations but ultimately falls between 4 m and 5 m.

The material properties assigned to the structure mimic those of common timber species (Young's modulus of 105 MPa and yield strength of 0.13 MPa). The member cross-section is set at 70 mm wide and 30 mm thick. Together, these properties and dimensions describe a thin wooden beam that is flexible and can bend considerably without breaking. The gridshell is modelled using what is known as the continuous lattice assumption. This assumption is merely a simplification used to streamline the analysis and states that a single layer gridshell can be modelled with all its beams in one continuous plane. A single layer gridshell is actually made up of two layers of stacked beams, and the joints have their own unique stiffness. This naming convention is slightly misleading, as a single layer gridshell is made up of two layers of beams. However, two layers of crossed beams are required to create a single lattice, hence the nomenclature. Because this model assumes that the lattice lies in one continuous plane, rather than two stacked planes, the joints are modelled as having the same stiffness and material properties as the rest of the lattice, in this case, wood. Despite these assumptions, a continuous lattice shell and a true single layer shell exhibit the same overall trends and yield results within 15% of one another (McCormick et al. 2003). This study seeks to illuminate trends and suggest near-final designs for gridshells; therefore, this margin of error is acceptable. Once a final design is selected, a higher fidelity model should be used to verify performance prior to construction.

3.2 Parametric Variation

During the parametric study, the grid density varies from "16 by 16" to "30 by 30." Five bracing schemes are analysed: unbraced, continuous fully-braced, discontinuous fully-braced, continuous half-braced, and discontinuous half-braced. The bracing schemes are defined as "half" or "full," depending on whether all or only half of the grid squares are braced, and "continuous" or "discontinuous" depending on whether the additional members brace one or more than one cell, see Fig. 3. The cross section, support conditions, and entrance arch height are held constant.

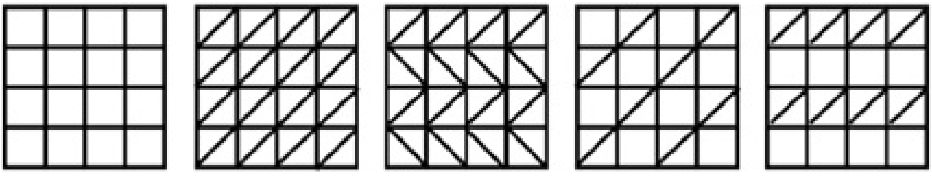

Figure 3: (*left to right*) *Bracing layouts – unbraced, continuous fully-braced, discontinuous fully-braced, continuous half-braced, discontinuous half-braced*

Figure 4: (*left to right*) *Load cases – symmetric distributed load, asymmetric distributed load, centred point load, off-centred point load*

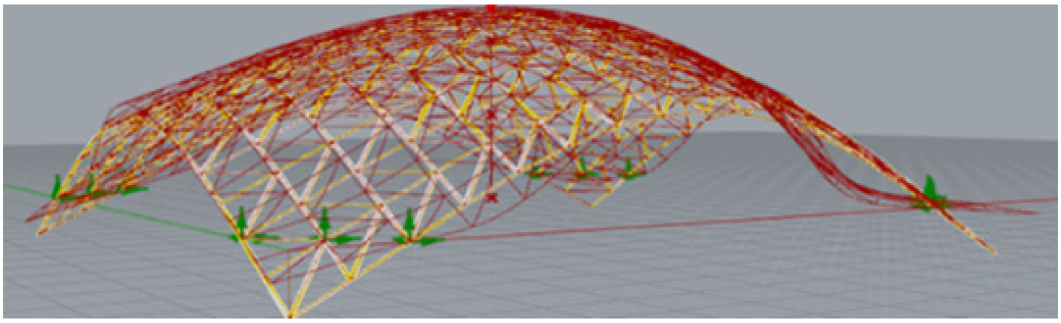

Figure 5: *Lowest buckling mode failure of a "20 by 20", discontinuous half-braced shell under a centred point load*

Each iteration of the structure is subjected to four load cases: a symmetric distributed load, an asymmetric distributed load, a centred point load, and an off-centred point load, see Fig. 4.

4 RESULTS

Taken as a large data set, the results of the parametric variations demonstrate how the shell performs under various loading scenarios and how different bracing schemes impact its performance. The failure mode studied in each iteration is global buckling, specifically the lowest buckling mode. A nonlinear, large deformation analysis is utilized to analyse each structure. This type of analysis iterates structural deformation as the solution converges, thereby mimicking real behaviour more closely than a first order, linear analysis. The buckled behaviour of the shells varies slightly based on the applied load case. Figure 5 shows an example of global buckling failure of a "20 by 20", discontinuous half-braced shell subjected to a centred point load. Note that the buckled shell is superimposed over the unbuckled shell.

4.1 Symmetric Distributed Loads

In the built environment, gridshells are likely to encounter symmetric distributed loads such as self-weight, cladding weight, and precipitation loads. These loads affect the entire structure in a balanced and distributed manner. When subjected to symmetric distributed loads, the strength of the structure varies primarily with bracing scheme. As expected, additional bracing material improves structural performance. Adding a half-braced scheme to the shell improves load carrying capacity by an average of 27%, for a 34% increase in weight compared to the unbraced shell. Similarly, the maximum load carrying capacity of the fully-braced shell shows an average increase of 53%, for a 66% increase in weight, compared to the unbraced shell. In both cases, every 1.0% increase in strength is associated with a 1.25% increase in weight. Increasing the grid density has little effect on the shell's strength and accounts for only small improvements in structural performance.

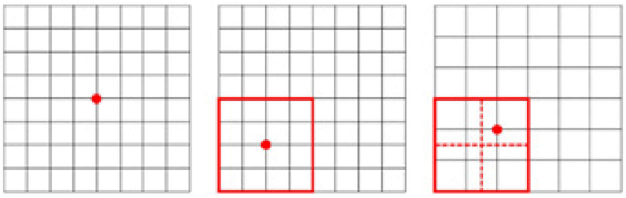

Figure 6: (left to right) Point load application – centred, off-centred (true), off-centred (closest).

4.2 Asymmetric Distributed Loads

In addition to symmetric distributed loads, gridshells are likely to encounter asymmetric distributed loads in the form of wind pressure or unequally affixed cladding. These loads are distributed over a large area but affect the structure in an unbalanced manner. This load case is defined as a load applied evenly over one half of the structure, thereby creating an asymmetric distributed load. Once again, global buckling failure dominates the structural response compared to local buckling. Additional bracing improves the load carrying capacity of the shell similar to a gridshell subjected to a symmetric distributed load, see above. Increasing the grid density under this loading scheme results in a loss of strength and worse performance.

Point Loads

Gridshells can be subjected to point loads when items are hung from shells' joints or individuals climb atop the shells for maintenance. Point loads are concentrated in a single location rather than spread over a large area. A centred point load is applied at the central intersection of the structural lattice. An off-centred point load is applied in the centre, or nearest centre, of a single quadrant of the structural lattice. If a central node is not present within the quadrant, the next closest node to the centre of the structure itself is used as the load application point, see Fig. 6.

Subjected to either of the point loads, the strength of the shell improves as grid density increases. Furthermore, any additional bracing also improves the shell's performance, regardless of the type of point load.

4.3 Continuity

This section takes a holistic view of the results of each of the load cases to understand how the continuity of bracing schemes affects structural performance. Considering fully-braced shells, the continuity of the bracing did not have a significant impact on structural performance. Both continuous fully-braced schemes and discontinuous fully-braced schemes consistently produce results within 10% of one another for all types of applied loads. However, continuous half-braced schemes consistently exhibit better performance (10 out of 12 cases), regardless of load case or grid density, than discontinuous half-braced layouts.

5 APPLICATION OF RESULTS

The results of the study yield trends describing the behaviour of a small gridshell under various load cases as grid density and bracing scheme are altered. These trends serve as a design guide to adapt gridshells for broader use. There is not a "one size fits all" solution when it comes to gridshell design. For example, improving the shell's failure resistance with respect to asymmetric loads can be brought about by decreasing grid spacing, yet improving the shell's failure resistance with respect to point loading requires the opposite. Furthermore, the strongest shell in an absolute sense might weigh too much for its intended application. As a result, the data must be interpreted based on the characteristics most important to the problem at hand.

In this paper, the results are used to help develop a mobile pavilion for HA/DR. Current products marketed as deployable pavilions weigh between 50 N/m^2 (large, lightweight tents) and 600 N/m^2 (ready-made concrete structures) (Operator's and Unit Maintenance Manual 1999, Concrete Canvas Limited 2018). As a result, a weight competitive structure might fall between 50 N/m^2 and 75 N/m^2. In this study, grid densities between 18 and 22 fit that weight category. Within these regions, ideal performance zones can be specified based on the demands placed on the structure. In this case, relevant building codes such as the International Building Code and Sphere Handbook are used to determine the limiting load cases. For this structure, the Attica region of Greece is used to calculate wind and precipitation loads.

Note that in Fig. 7, the ideal performance zones for an HA/DR application are indicated with boxes. An ideal shell falls within the box. Performance beneath the box is unsafe and performance above the box is superfluous. The red markers on the graphs represent a continuous half-braced gridshell with a grid density of 20. This is one of the grid densities tested with a continuous half-braced scheme, and it consistently outperformed the discontinuous half-braced scheme with the same grid density.

In this example, discontinuous half-braced and continuous half-braced schemes both fall within the ideal performance zones, while both fully-braced schemes fall within or above those same regions. For the same amount of material, the continuous half-braced scheme applied over a gridshell with a grid density of 20 outperforms its discontinuous counterpart. Additionally, continuous bracing is easier to install on the structure during the construction process compared to discontinuous bracing, representing an additional advantage. As a result, a 15 m by 15 m clipped square gridshell with a grid density of 20 and continuous bracing over half of the grid spaces is considered the best fit for the HA/DR scenario described throughout this paper. It is important to realize that the results are scalable in size, and that based on which characteristics are considered most important, there may be other gridshell designs well suited for HA/DR.

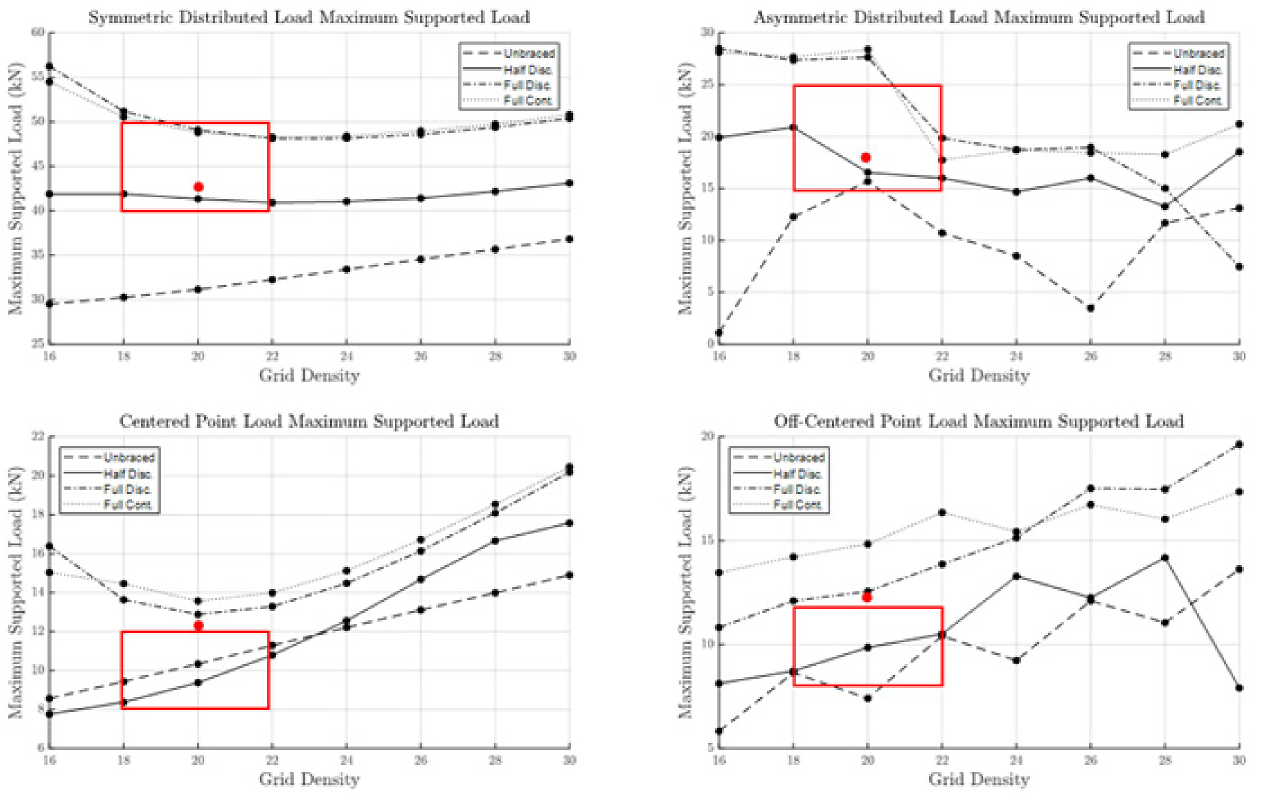

Figure 7: Summary of structural performance for each load case with the desired performance zones designated boxed and a "20 by 20", continuous half-braced gridshell indicated with a dot marker

It is worth noting that with 64 people spread evenly across the structure mentioned above (1.875 m spacing between individuals), each would need to apply only 160 N of force, equivalent to lifting a 17 kg weight, to raise the shell. Scaffolding will likely be necessary during the construction process to help maintain the form, but with only 17 kg of mass allocated to each person, construction without the use of cranes or heavy machinery would be possible (Naicu, Harris, & Williams 2014). Additional personnel would further reduce the force per individual.

When designing a gridshell, the choice of a bracing pattern and grid density is a combinatorial problem, which makes any optimization algorithm increasingly difficult to fashion. Instead, this paper suggests that given a general gridshell structure subjected to various load cases, bracing geometries, and grid densities, designers can choose from the results a performance region suited to their needs. By understanding the overall trends of the structures in questions, engineers can converge on solutions more quickly and can build a better understanding of how various parameters impact structural performance. Once a gridshell is selected, higher fidelity analysis that considers true single layer behaviour versus that of the continuous lattice assumption, joint stiffness, horizontal loading, and anchoring conditions must be completed.

6 CONCLUSION

Gridshells are designed to withstand many load cases, but regardless of the load case, the dominant failure mode is often global buckling. Proper bracing helps to stiffen and strengthen these structures in order to withstand symmetric and asymmetric distributed loads, as well as various point loads. Across each of the load cases studied in this paper, additional bracing has the greatest effect on improving load carrying capacity. Increasing the grid density is quite effective in improving the structure's resistance to failure under point loading. The continuity of the bracing shows little variation between fully-braced schemes, but continuous half-braced schemes consistently outperform discontinuous half-braced schemes. Using this data and methodology, designers can focus on structural characteristics based on the intended application of the shell. By selecting the structure that best fits the specified performance metrics, the data and methodology presented here can help designers select gridshells that are well suited for applications beyond their traditional niche. This paper makes the case that gridshell structures can be adapted to support large-span shelter needs in HA/DR scenarios.

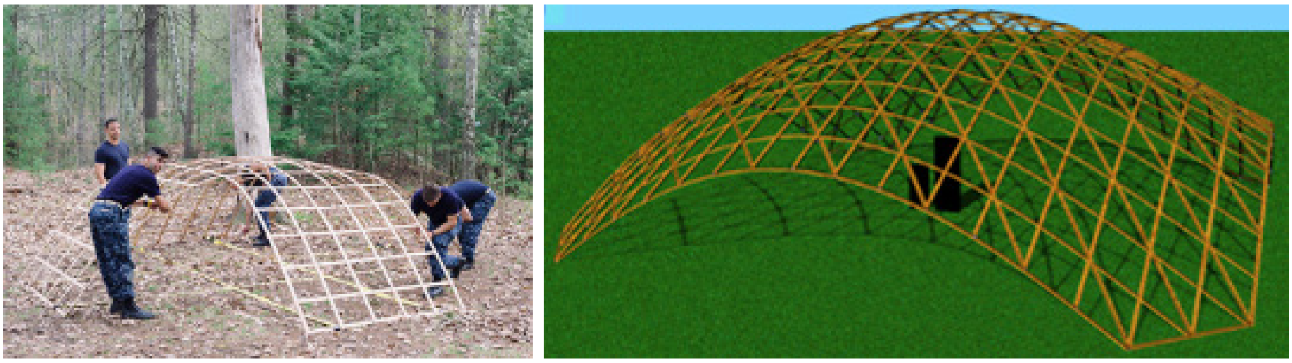

Figure 8: (*left to right*) *Prototype of HA/DR gridshell – at the Harvard Humanitarian Initiative in* 2017 *and as a full-scale computer rendering*

7 FUTURE WORK

Research at the U.S. Naval Academy, coordinated by Professor Samar Malek over the past seven years, with the input of Professor Dave Polatty at the U.S. Naval War College, and numerous students, has already made strides to establish gridshell structures as potential solutions for large-span HA/DR shelters. Small-scale prototypes have featured at the Harvard Humanitarian Initiative, see Fig. 8, and continue to draw interest from the U.S. Naval War College Humanitarian Response Program. A large-scale prototype is ready for construction in the spring of 2021. Current research efforts have advanced the possibility of employing gridshell structures in HA/DR, yet additional work to investigate cladding, construction mechanics, and supply chains remains relevant.

With additional research and development, gridshell structures have the potential to serve in a variety of settings as a lightweight, natural, portable, adaptable, and efficient means for providing large-span shelter to remote regions. Gridshell technology can be refined and codified into design rules of thumb in order to lower the barrier to entry on these structures. By improving understanding and simplifying design approaches, these structures could serve to fill a much-needed role in HA/DR efforts and beyond as portable large-span structures.

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9 REFERENCES

Adriaenssens, S., Ney, L., Bodarwe, E., et al., (2009) Dutch Maritime Museum: Form-finding of an irregular faceted skeletal shell- Part b. In: A. Domingo and C. Lazaro, eds. *International Association for Shell and Spatial Structures Symposium,* Valencia, Spain. pp. 1356-1366.

Concrete Canvas Limited, (2018) *Concrete Canvas Shelters.* [Viewed 19 July 2019]. Available from: https://www.concretecanvas.com

Disaster Response in Asia and the Pacific (2013) *United Nations Office for the Coordination of Humanitarian Affairs* [online]. [Viewed 23 July 2019]. Available from: https://www.unocha.org/sites/unocha/files/dms/ROAP/Promotional%20Materials/The%20Guide-Web-FINAL.pdf

Edilsider SpA., (© 2020) *Edilsider: The Reference Point for Your Operational Needs.* [Viewed July 20 2019]. Available from: https://www.edilsider.com/edilsider-42.html

Figures at a Glance (2020) *United Nations Office for the Coordination of Humanitarian Affairs* [online]. [Viewed 25 July 2020]. Available from: https://www.unhcr.org/uk/figures-at-a-glance.html

Happold, E. & Liddell, W., (1975). Timber lattice roof for the Mannheim Bundesgartenschau. *The Structural Engineer*. 53, 99–135.

Knippers, J. & Helbig, T., (2009) *Recent Developments in the Design of Glazed Grid Shells. International Journal of Space Structures* [online]. 24, 111-126. [Viewed 20 February 2018]. Available from: doi: 10.1260/026635109789043205

Liddell, I., (2015) *Frei Otto and the Development of Gridshells. Case Studies in Structural. Engineering* [online]. 4, 39–49. [Viewed 19 July 2019]. Available from: doi: 10.1016/j.csse.2015.08.001.

Malek, S., Wierzbicki, T., & Ochsendorf, J., (2014) Buckling of spherical cap gridshells: A numerical and analytical study revisiting the concept of the equivalent continuum. *Engineering Structures.* 75, 288–298.

McCormick, S., Besjak, C., Korista, S., et al., (2003) Shell of Steel. *Civil Engineering—ASCE.* 73, 68–73.

Naicu, D., Harris, R. & Williams, C., (2014) Timber Gridshells: Design methods and their application to a temporary pavilion. In: A. Salenikovich, ed. *World Conference on Timber Engineering,* Quebec City, Canada.

Operator's and Unit Maintenance Manual, Including Repair Parts and Special Tools List for Modular General Purpose Tent System (1999) Washington D.C.: Department of the Army.

Project for Public Spaces, (2018). *What can public spaces offer to the globally displaced*? [online]. Project for Public Spaces. [Viewed 16 July 2019]. Available from: https://www.pps.org/article/refugees-and-public-space.

Schlaich, M., Burkhardt, U., Irisarri, L., et al., (2009) Palacio de Comunicaciones- a single layer glass grid shell over the courtyard of the future town hall of Madrid. In: A. Domingo and C. Lazaro, eds. I*nternational Association for Shell and Spatial Structures Symposium*, Valencia, Spain. Madrid: International Association of Shell and Spatial Structures, pp. 1338-1348.

Sischka, J., (2000). Engineering the construction of the Great Court roof for the British Museum. In: M. Barnes, M. Dickson and T. Telford, eds. *Widespan Roof Structures.* London: ICE Publishing. pp. 199–207.