Frei Otto's Pneumatic Experiments for Humanitarian Design

Rob Whitehead

Associate Professor, Department of Architecture, Iowa State University

Abstract

This paper will explore the intersection of building technology and humanitarian design-science research by looking at Frei Otto's pneumatic experiments. The purpose of the study is to contextualize our contemporary demands for humanitarian design work by reflecting upon the manner by which Otto integrated an ambitious design ideology with an elevated and innovative technical acumen. Constraining the investigation to Otto's work, particularly his relatively unknown early work with pneus, provides a useful exploration of design-science approach that connect design and technology—an approach that is useful to understand for contemporary pedagogical applications.

Otto himself connected his career to humanitarian work. Shortly before his death in 2015, Frei Otto vowed to, "…use whatever time is left to me to keep doing what I have been doing, which is to help humanity." The paper will explore the complicated manner by which Otto's design and research contributed towards humanitarian design (or not), both in process and content. Although Otto's desire to "build light and keep mobile" *can* be applicable for relief and recovery structures, he intended it more broadly. His operational ideology for lightweight structures sought to connect design, nature, and humanity; but his design-research work was intentionally acontextual. Instead of producing a particular product building, he explored a realm of structural typologies to determine how forms and construction could be leveraged to help address a myriad of other humanitarian issues. The work *wasn't* intended explicitly to intervene in traditional humanitarian relief or recovery efforts.

However, at the earliest stages of his career, his book, *Tensile Structures, Volume 1 (1962)*, Otto's included hundreds of proposals for innovations in pneumatic structures, many that seemed explicitly created to address various humanitarian needs of food, water, infrastructure, and shelter for inhospitable locations. The paper will show the connections between the design intentions and technical explorations that led to this innovative pneumatic proposals (many as yet, unrealized). The manner by which the work was conceived and studied is relevant to our contemporary concerns in practice and pedagogy so the paper will concluded with observations and recommendations for connections that can be made.

Keywords: Frei Otto, Pneumatics, Humanitarian Design, Lightweight Structures Pedagogy

Humanitarian Intentions and Design Technology

Beginning in the 1950s, design-science researchers searched for innovative design solutions that would provide tangible assistance to humanitarian efforts. They believed design could make a difference. Despite spurious efforts that erroneously conflated the search for "better shelters" as the sole expression of this work, formative progress came from experiments that more generally applied innovations in building technology towards the advancement of this work.[1] The connections are evident: constrained conditions can amplify the importance of the leveraging design tactics, technical principles, and evaluative standards towards performance (i.e., maximized material utilization, rapid deployment, resiliency, etc.). For designers like Frei Otto (1925-2015), the work was more than just a technological challenge; it was inspired by broader ideologies of humanity and natural systems, bound together by philosophical perspectives about design.

Otto had an ambitious ethical framework. His desire to "build light and keep mobile" was an attempt to create transparent, democratic, and more equitable access to shelter for everyone.[2] For Otto, all design was humanitarian. He sought conjoin material efficiencies and form with natural systems, and he became renowned as a pioneer in the design, analysis, and construction of large-scale lightweight structures (Figure 1).[3] His legacy is more complicated; the unique formal qualities of his built work often overshadowed his deeper intentions.

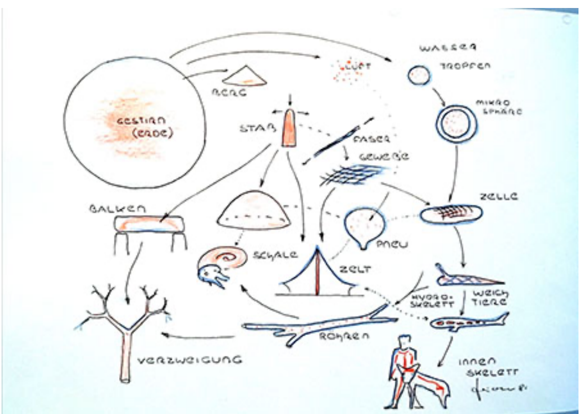

Fig. 1. "Structures and Biology", Otto, 1985.

Shortly after his death, the 2015 Pritzker Prize award jury described Otto as a speculative "…inventor, form-finder…and creator of memorable buildings and spaces."[4] Yet weeks before, Otto summarized his career differently. He described his desire to, "design new types of buildings to help poor people especially following natural disasters and catastrophes" even though he'd only had a few commissioned projects to do so. The bulk of his largely unknown humanitarian work was in the realm of design-science research in pneumatics. This work started his career six decades earlier and fueled an ongoing search for a deeper connection between humanity and building technology.

The manner by which building technology and humanitarian design efforts are connected in practice and education is of critical contemporary concern. This paper will explore the intersection of building technology and design research by looking at Otto's work intended explicitly for humanitarian relief, recovery, or resiliency. The unique qualities of lightweight structures will be discussed as a way of demonstrating their alignment with humanitarian challenges. The paper will explore ways to connect Otto's work to a pedagogical model of design-science that ties authentic and purposeful inquiries found in humanitarian design efforts back to building technology.[5] By purposefully constraining and situating the learning with lightweight-structures, a process of case-study analysis and design-science research can be actively constructed around the work modeled by Otto.

Formative Forms (without Function)

Otto's describes his technical and ideological interest in lightweight structures as deriving from many formative early experiences. Throughout his education, he searched for the same type of innovation of purposeful forms found in modern planes and ships—including their ability to adapt to environmental conditions. But his motto, "with lightness against brutality" had political and social implications as well as it was intentionally antithetical to the solid, earthbound, and "permanent" buildings proposed by the German National Socialists. [6] His work was always more than tech-centric.

In 1950, as part of his architectural education (TU-Berlin) Otto studied a semester of at the University of Virginia and met with several influential architects and structural engineers across the U.S. that specialized in tensile structures. Otto learned of the potential for lightweight structures to minimize mass and materials if the building form was creatively and technically correspondent.[7] This work became the focus of his ambitious doctoral dissertation in engineering, "Das hängende Dach" [The Suspended Roof] for a pneumatic roof that covered a "City in Antarctica." At this time, the thesis was completed in 1954, engineering work in tensile structures was highly specialized, and primarily relegated to suspended bridge structures, not membranes or building enclosures so his thesis was a novel and important contribution to the field (Figure 2).[8]

Fig. 2. "Mining in the Arctic", Otto, 1953.

Otto encountered many unknowns during his thesis research. He contacted Peter Stromeyer, the chairman of the largest tent manufacturing company in Germany, L. Stromey & Co. in an attempt to understand more about membranes. By invitation, Otto visited the company in-person and later reflected that their first week together in 1953 was "the most productive working weeks in his entire life."[9] In order to understand how to work with membranes, they began with "the simplest" possible forms and with the assistance of crafts-people at Stromey, they would fabricate and test prototypes of their forms.[10] Their professional relationship lasted decades.

In the ensuing years, Otto was traveling, teaching, researching, and collaborating with contemporaries in this developing field. Because he didn't have clients or commissions, Otto explored this work more generally. Because of these limits, the structures he designed weren't derived from human internal functions but from the limits found in materials, form, and behavioral analogies with nature. Instead of starting with a function, he'd start with a form and explore ways to make it a useful enclosure, often in harsh or unexpected places.[11] This cutting edge research in architectural structures placed Otto among a growing international field that came to known as design-science.

Design-Science (for Humanity)

Design science involves the systematic creation of knowledge about, and with, design. It is more commonly known as a scientific framework for discovery-by-design, but it is more than just design.[12] In 1950, Buckminster Fuller (1895-1983) coined the term "Comprehensive Anticipatory *Design Science*" to describe his ethic-driven design sensibility that embraced humanity's ability to actively participate in shaping its own evolution. Fuller characterized it as a comprehensive and process of future-systems thinking and artifact creation that aligned with nature's underlying principles, while remaining science-based and subject to empirical verification.[13] Fuller and Otto met in 1958, while Otto was researching and writing *Tensile Structures, Volume 1*; their relationship bonded over the potential connections to biological and natural systems and continued for decades after.[14]

Various approaches were established by the earliest contributors: Fuller saw the promise of creating an ideal structural typology, the geodesic dome, with beneficial physical qualities that could be implemented universally. Konrad Wachsmann (1901-1980), (a friend of both Fuller and Otto), focused instead on innovations in construction procedures of prefabrication and standardization of connections to ease the burden of assembly.[15] Otto took Fuller and Wachsmann's search for adaptable and transportable structures to a systems-level by focusing on the inherent benefits of lightweight-structures, in particular, pneumatics.

Early Pneumatic Experiments (1954-62)

"Soon (pneus) became the only forms I could see in everything that was alive…my study of pneus had introduced me to a completely new world of forms…" - Frei Otto, 2004[16]

Pneumatic membranes (pneus) are containers of space that use differential pressure only for support. They are nearly weightless, they can be easily deployed, and can theoretically span for miles using membranes and cables. The limitations on their capacity are economic, social, and energy-based rather than structural. But finding the forms and aligning them with forces and managing the various stresses was a scientific field that had rarely advanced based balloons and dirigibles. Otto pioneered the integration of these experiments into architecture (Figure 3).

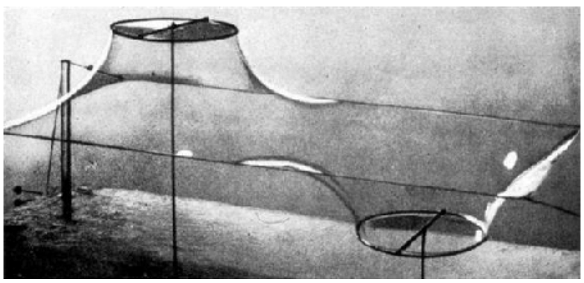

Fig. 3. Soap Bubble Experiment

From 1957-1960, through funding provided by Stromeyer, he documented a set of experimental pneumatic structures for his book *Tensile Structures, Vol. 1* (1962). Otto focused on pneumatics, or inflated membranes, because of their resemblance to biological forms and organic life. He argued that structural forms derived from technical logic would become, "…nearer to organic life."[17] The book's premise was simple. Otto experimented with various pneumatic forms (e.g., balloons, sails, cushions, cones, etc.), worked to understand their structural principles, and assigned performance-based advice about their potential use .

The amount of information presented, and the creative imagination behind it, is daunting in scope. The first chapter features several hundred illustrations and photographs of speculative pneumatic form models (including the famous soap bubble experiments). The book's contributors sketched, built models, and developed calculations to show the potential viability for the work. Critical structural design issues related to each variation on the pneumatic were explored (ranging from form-finding to stress analysis), and then Otto would suggested potential uses for each form. This "form-first" method is worth noting and exploring.

Although the illustrations show the work placed in myriad of physical contexts and being used for various purposes, the work was designed to be speculative, and intentionally *not* derived from any particular context or function. This isn't to say that context or function didn't matter; far from it. For example, to illustrate the value of pneumatics as a light, adaptable, and innovative structural system, they were intentionally illustrated in remote and harsh physical settings such as: floating islands of pneumatic settlements within bodies of water, remote installations in the arctic (a study he'd return to in 1971), and even extraterrestrial regions.

Many of his illustrations suggest functional applications related to food, water, shelter, and infrastructure. But the accompanying text avoids nearly any discussion of the relationship between the form and internal functional. By intentionally separating form from function, Otto suggests that certain forms could be used to solve various, even disparate functions at various scales. He describes several "new structures": pneumatically stretched skin with internal drainage, new containers for liquids, and new methods of creating vehicular and natural infrastructure. [18] Although his descriptions sound clinical, his proposals for each were substantial.

The internal drainage system solved critical structural issues that had previously limited the application of long-span pneumatics. Large spans were theoretically possible, but practical limitations on membrane stress allowances had always been the limiting factor in engineering.[19] Otto's proposal reduced the overall spans by placing regularly-spaced tie-downs, creating a form that resembled, if inverted, a shell structure on columns. By understanding the form-finding process and the consequences of membrane stresses at the internal drains, Otto created a structure that could cover more ground with more economical shorter spans. Otto suggests that a greenhouse would be an ideal function and demonstrates how water could be sustainably collected, and re-used, at the tie-down points (Figure 4).[20]

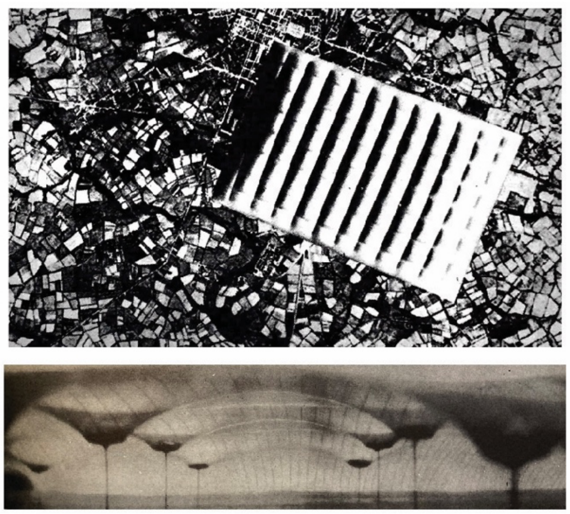

Fig. 4. Pneumatics with Internal Drains (Greenhouse), 1957-62

The various applications for the containers for liquid storage were shown to be progressive alternatives to the permanent water and food storage and distribution systems around the world because they were light and adaptable. Specifically, Otto shows how food and water could be transported easier, and stored faster, than traditional silos and water towers—a distinct advance for sudden accumulations of both in remote locations. He shows their ability to be suspended from rods for easy access from below and presents them as beautiful visual alternatives (Figure 5).[21]

The proposals for the lightweight and transportable infrastructural systems presented a radical rethinking of resiliency and recovery methods for roads, bridges, and dams that would inspire decades of subsequent research by others. He proposed balloon supports for portable landing strips in the water, a balloon-based alternative foundation system for suspended bridges in the water, pneumatic tunnels for underwater transportation, pneumatic tubes as bridge supports, and massive walls of deployable pneumatics for flood control measures and damming (Figure 6). [22]

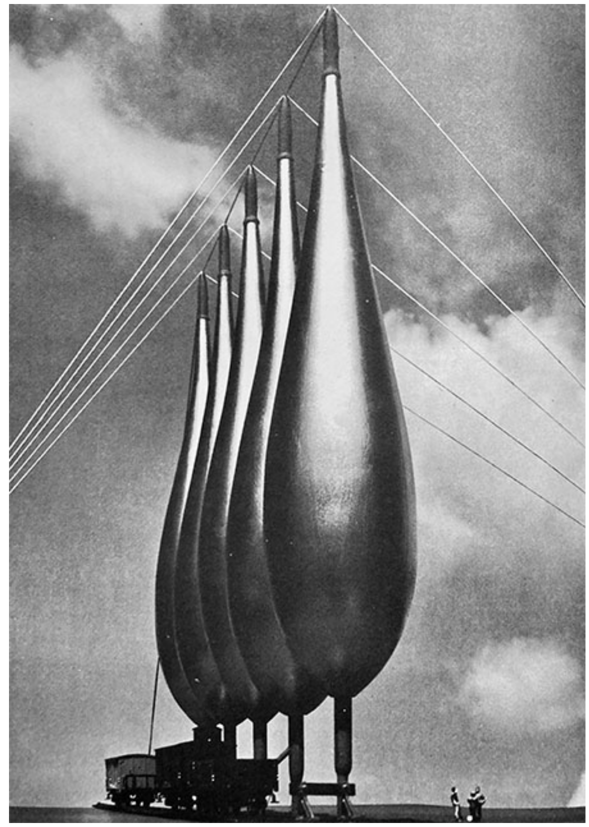

Fig. 5. Deployable Pneumatic Silos, 1957-62

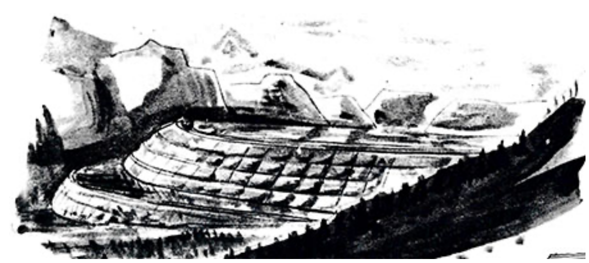

Fig. 6. Deployable Pneumatic Dams, 1957-62

The design-science method obligated Otto to propose data and calculations that supported the viability of his proposals. The second chapter presented descriptions and calculations for the basic structural principles of the various pneumatic types he'd proposed. These were intentionally more general and not tied to any specific proposal (i.e., there weren't separate calculations for pneumatics in outer space).The third chapter proposed new types of foundations that would correspond with the unique qualities of pneumatics such as: reduced weight, resistance to lateral forces, and their ability to be deployed and relocated rapidly.

Overall these proposals ranged from practical to fantastic; but they were all *experiments*. The relationship between the hypothesis and verification in design-science can be complicated, particularly when the scope of the experiment intentionally shed certain boundaries or control points. This was the uniqueness of Otto's approach to design-science research: ostensibly he'd propose and verify the structural capacity of acontextual elements (e.g., here is how a pneumatic cone works) *but* he'd also show the potential applications for the work within a setting of operations that would be too complicated to verify and yet, aspirational in important ways. He wasn't looking for a single solution or a universal architecture but was developing a tested language for others to use.

The fact that he suggested humanitarian-based uses for structures while also maintaining a critical distance from their *actual* deployment and use is confounding, but elucidative. This design research wasn't agnostic of world events, or design's potential to improve them, but the myriad of complications involved in actually implementing and operating these buildings as proposed were factors that were far outside of a verifiable equation. Otto warned about over-estimating the impact of buildings alone to make a difference, "…we should be aware that constructions do not actually have anything to do with people."[23] It perhaps points to the conundrums between research and practice that marked Otto's ensuing career, and the difficulties of integrating his research into practice.

Transitions in Research and Practice (1962-88)

"Pneumatic structures not only permit solving old problems, but they also open the way to entirely new applications, which could not have been possible without them." – Otto, 1962[24]

Following the publication of *Tensile Structures, Volume 2* in 1967, Otto's was known as one of the world's leading experts in pneumatic research—but not practice. In fact, in a practice career that spanned decades, Otto would design only *one* pneumatic structure for a modestly-sized lab.[25] Otto had seemingly moved on from pneumatics in his research and the industry had moved on from him.

In 1964, Otto founded the Institute for Lightweight Structures research group at the University of Stuttgart (ILEK) on the principle of inter-disciplinary cooperation including architects, engineers, biologists, anthropologists, and historians. ILEK completed large-scale research experiments by modeling various lightweight structures and translating them to viable buildings, blurring the line between research and practice. But the proposals shifted from pneumatics towards tent and membrane structures including Otto's best known works, the German pavilion at Expo '67 and the 1972 Olympic stadium roof in Munich.

By the time he was asked to give the closing remarks at the IASS 1st International Colloquium on Pneumatic Structure in 1967, it was clear that the pneumatic design industry had already evolved towards either commercial or artistic interests, but not humanitarian. Speakers Walter Bird, Dante Bini, and Heinz Isler had all developed practical pneumatic structural systems that could be purchased, while Victor Lundy and Graham Stevens presented artistic installations they'd created to challenge the "normality" of a traditional pneumatic shelter.[26] Engineer Cedric Prince expressed constructive pessimism of the way pneumatics were primarily being used to solve, "…normal structural and shelter problems" perhaps as a reference to Otto's seemingly forgotten proposals. But, Otto's closing comments were primarily reflective of the technical challenges facing the industry, and not critical of ideological scopes presented.

But this wasn't the end of Otto's engagement with pneumatics. In fact, during the later stages of his career, Otto guided the ILEK's research and publication of the IL-Publication series for lightweight structures. It included provocative essays, images, and research questions for architects and structural engineers. They would produce six different publications on pneumatics from 1971-1985; Pneus were the most popular topic. 1971's IL2, "City in the Artic," was an update to Otto's thesis.[27] For this project, Otto collaborated with Kenzo Tange and Ove Arup on a thoroughly developed proposal for a 2km wide pneumatic dome enclosing a city of 40,000 people. It was ambitious, but it's viability was closely tied to operational systems and functions (a deviation from Otto's earlier preferred method of design-research). It was widely criticized; eventually even by Otto himself.[28]

Ensuing IL publications about pneumatics became more experimental, igniting entirely new debates about the capability of pneumatic structures to transcend shelter and work towards more radical relationships with nature and humanity. This work includes: IL19 "Growing and Diving Pneus" (1979), "Pneu and Bone" (1985) and IL12 "Convertible Pneus" (1975). Visually, IL12 is stunning—it features 1,000+ drawings of proposed pneumatic projects (including Otto's earliest work)—but the theoretical underpinnings behind the work is where the real design-science scholarship rests. The publication includes re-illustrations of many of the humanitarian proposals, just re-classified by form. IL12 proposes that pneumatics could be classified by the complexity of the operations they fulfill: 1st Generation: The "Balloon Analogy", 2nd Generation: The "Machine Analogy", and 3rd Generation: The "Biological Organisms." As before in his work, humanitarian operations weren't explicit, but the connection between pneumatics and the potential benefits to human existence were paramount, particularly for 3rd Generation pneumatics.[29]

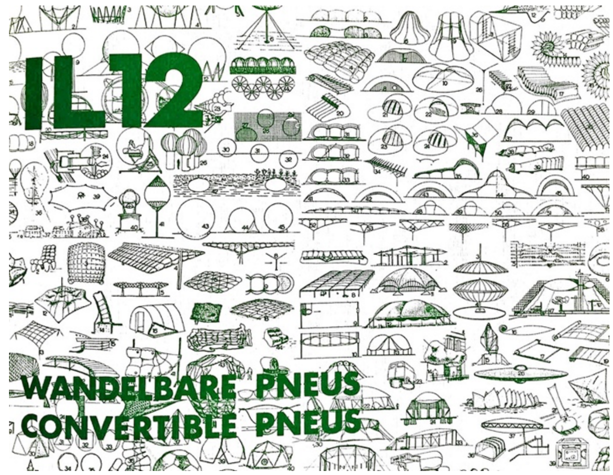

Fig. 7. IL12, Convertible Pneus, 1975

Connection to Pedagogy: Ideas and Technology

Otto's background and pneumatic experiments are presented as a way of contextualizing the possible breadth of available information to integrate into a humanitarian-based building technology course. Otto's research is contemporarily relevant in the ways it intersects design with the most important challenges facing the world today: food, water, energy and infrastructure.[30]

Structural design work aligns ideologically in obvious and practical ways with humanitarian challenges in ways that are easy to connect pedagogically. Responsive solutions would need to align structural form with forces, select appropriate materials, and devise strategies for effective fabrication and assembly—all essential structural design principles that could also be evaluated.[31] This learning is enhanced through the design-science method when the "how-to" is connected with the "what" and the "why." For example, using Otto as a model, if one starts with an ideology of lightness, efficiency, and adaptability, one can justify the selection of tent/membranes structures, which in turn would identify a particular set of technical skills / knowledge that need to be modeled and tested. As a whole, the inclusion of a humanitarian challenge gives the work a purpose beyond simply standing firm.

Otto's particular approach to design-science methodology may be a useful to teach, or emulate. By constraining his experiments to one type of structure, and even by separating his design from a particular sites, communities, and/or functions, he was able to focus specifically on potential applications for technically resolved forms. Although there are draw-backs to not engaging one community directly with the work at a micro-scale, this mode of design-science allows for more macro explorations that may be useful given the inherent constraints of academia. Alternatively, this hypothetical, in-direct, advocacy approach may serve as a point of critique instead.[32]

Pedagogically it is important to contextualize the role and responsibilities of researchers. Researchers have always played an important role in supporting the efforts of humanitarian agencies by producing topic-specific position papers and commissioned reports. Most policy-based research rarely proposes radical changes, but instead looks at ways of understanding and improving upon on-going efforts.[33] Design-science research *can* take a similar incremental approach. But disruptive and innovative solutions, like those proposed by Otto also play an important role; they present a tricky paradigm of "outsider influence" that is often problematic but innovation is essential in design. But Otto's approach has merits in the way it supports "local solutions to local problems" focusing on developing an open-source scope of design-research and general knowledge, not a product to sell.

There are unique benefits of integrating this scope of work into the structural design education of architects. By applying their technical knowledge towards a daunting, but important and realistic architectural challenge, they learn that the relative efficacy of their design interventions are inextricably linked with their realistic engagement with a broad range of technical encumbrances.[34] They contextualize the role of design and consider its larger purpose. Ultimately, the questions posed by Otto's work that link humanity, nature, and architecture are perhaps his lasting legacy. Before his death, Otto stated, "I will use whatever time is left to me to keep doing what I have been doing, which is to help humanity." The Pritzker jury summarized his influence, "Herein resides his deep influence: not in forms to be copied, but through the paths that have been opened by his research and discoveries."[35]

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