Design and construction approaches of shallow foundation in permafrost with an application for a 3D printed habitat on Mars

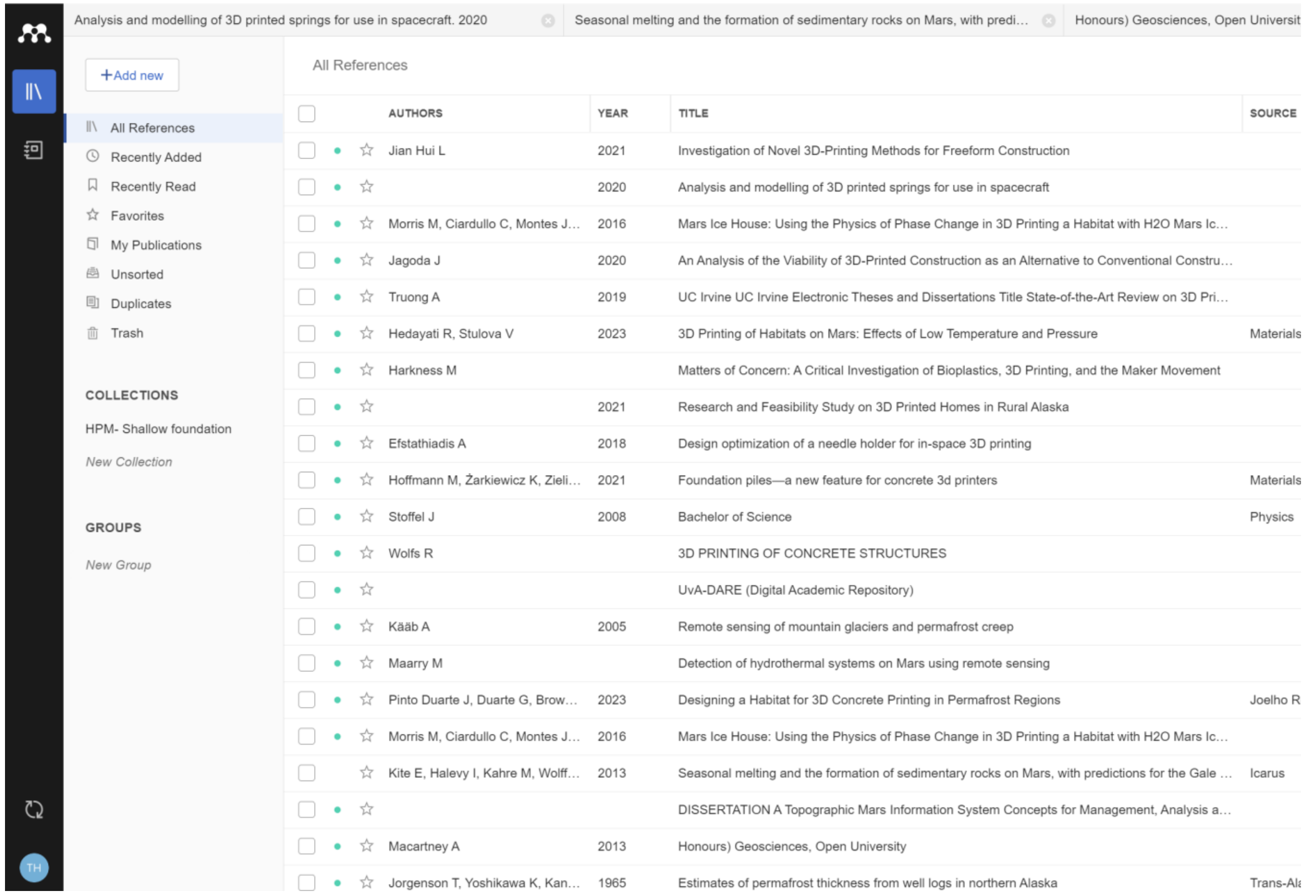
Tzu-Shou Huang

Honour Programme Masters Research

Literature Review

Keywords:

- Martin terrain conditions
- Nordic permafrost architecture
- shallow foundation
- historical and contemporary approaches
- Topological Interlocking assemblies
- Voronoi



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☐	●	☆		2020	Analysis and modelling of 3D printed springs for use in spacecraft	
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Abstract

Abstract:
The design and construction of buildings on Mars is a significant engineering challenge due to the complexities of the harsh and frigid environments, degrading permafrost, and limited construction materials and equipment. A novel exploration is to build habitats through 3-D printing. This paper presents the initial design and construction approaches of various foundations for the 3-D printed habitat on Mars.

Methods
First, Mars's terrain and possible environmental and seasonal changes are reviewed based on the available literature. The review discusses descriptions of the morphology of the surface on Mars and explains the thermal contraction of polygonal terrain (difference in lower and higher latitude), drainage/channel incision, and seasonal changes.

Second, the permafrost terrain between Mars and Nordic is compared to. The research investigates Nordic architecture foundation regulations and construction methods because of their similar permafrost condition, -10+ degrees temperature and "thaw-stable" and "thaw-unstable" danger possibilities to built infrastructure due to foundation heat transfer and seasonal changes. Third, the typical design and construction of shallow and deep foundations on permafrost construction regulations are reviewed through case study research in the Arctic and Nordic. Conventional shallow and pile foundations for 3D printing habitats are explored based on the recommended foundation design practice in permafrost regions. The initial design and regulations in Nordic countries' construction approaches are slurred pile foundations, driven piles, and shallow foundations, which are discussed, and examples of such foundations are presented. Besides the structural loads transmitted to the soil, thermal effects are also considered in the specification of design parameters to reduce heat transfer to permafrost due to seasonal changes.

Fourth, the research investigates other case studies of 3D printing foundations on Mars. One of the case studies is 'Designing a Habitat for 3D Concrete Printing in Permafrost Regions' by Jose Duarte (July 2023) from the University of Pennsylvania, exploring foundation options from 'raised from the ground', 'on the ground', and 'platform' to have a "crawl space" underneath to avoid heat transfer to permafrost.

Fifth, based on new foundation technologies to prevent thawing during seasonal changes (thermosyphon system, ventilated duct system, heat pump cooling system). This paper reviews how the new systems used in the Arctic and Nordic can be implemented into the Voronoi-based foundation. This research is a preliminary design document for foundations in permafrost for 3-D printing habitat on Mars.

Sixth, transformation from historical foundation examples to Topological Interlocking Assemblies; Cubes and tetrahedrons are assembled in mutually kinematically constraining planar configurations. These assemblies are capable of resisting external loads impacting perpendicular to the main load bearing direction due to force-locked interfaces between their elements. Given fixed boundary conditions the assemblies are able to resist high bending forces and even tension without any additional binding material like mortar.

Content

I have separated into Chapters

Chapter 1- Research on Martin terrain conditions

- Radiation

- polygon formation terrain/ icy terrain

- How are they formed And the 3 types of polygons + case study

-drainage and channel incision and channel

- seasonal changes and it's possible influence on foundation '

Chapter 2: Introduction to Nordic Permafrost

- What is Permafrost?

- Comparing Mars environment with Nordic permafrost architecture

Chapter 3: Historical Permafrost foundation and shallow foundation
  - Slurred Piles
  - Driven Pile Support
  - Types of Slab- On- Grade foundations

Chapter 4: Contemporary Permafrost architecture foundations

Chapter 5: Utilizing Nordic foundation construction methods into 3D prints on Mars
- Literature review about other design foundations
- Their concepts and developments

Chapter 6: More technical : Types of Slabs
- Strip Footing
- Pad Footing or isolated footing
- Combined Footing
- Mat or Raft Footing

Chapter 7: What technology is needed to prevent thaw during seasonal changes
- What is needed?
- Analyze of Modern Case studies
- Thermosyphon system
- Ventilated duct system
- Heat Pump Cooling system
-Foundation Preparation

Chapter 1a- Research on Martin terrain conditions

Introduction to Polygon formation / Icey Terrain

The goal of this work is a quantitative description of the morphology of the surface of Mars

smooth- similar to Amazonas Planitia- exhibiting an rms variation in typology of under 2m over 100km baseline.

Regional scale slopes is small, generally smaller than 3 degrees.

Why Mars terrain is compared to Nordic and Alaska

The permafrost zone underlies 80% of Alaska including continuous (29), discontinuous (35), sporadic (8), and isolated (8) permafrost. Permafrost is absent beneath 15% of the State, with glacier and ice sheets occupying 4% and large water bodies 1% of the area.

-average temp is below 0 degree, meaning a thick global cryosphere- never exceeds the melting point.

- Ice is abundant and in amount of the soil noticeably exceeds 50% by absent.

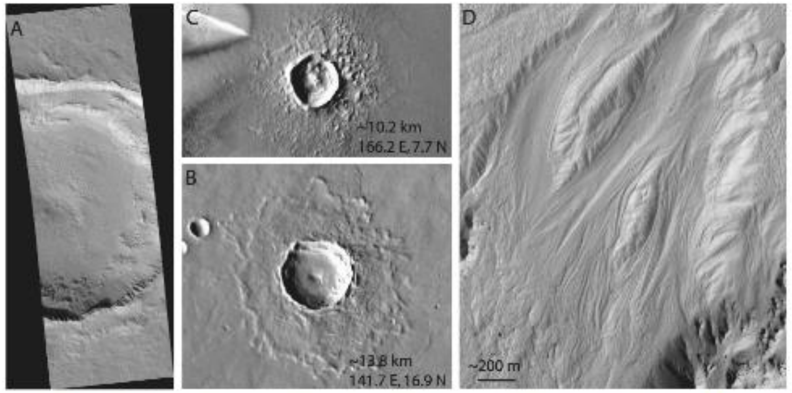


Fig. 14. Examples of craters with “dewatering” features. A. Pitted material on the floor of an unnamed crater. Image is HiRISE subimage PSP_004244_1970 (NASA/JPL/The University of Arizona). B. Context image for A. C. Context image for D. D. Wet debris flow around the central uplift of Zunil crater. Image is HiRISE subimage PSP_001764_1880 (NASA/JPL/University of Arizona). B and C are THEMIS images from JMARS (http://jmars.asu.edu).

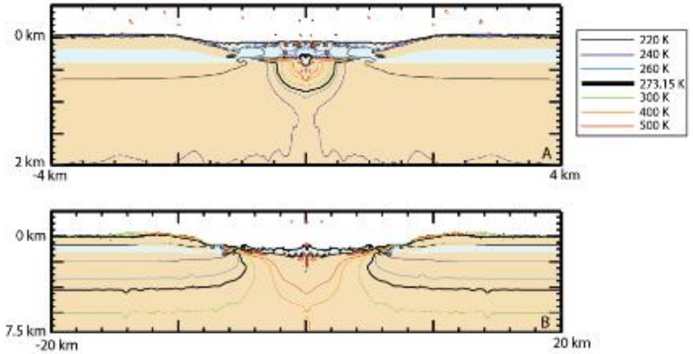


Fig. 15. Final temperature contours beneath craters formed by (A) a 200 m diameter projectile impacting at 10 km/s into a target with a 200 m thick ice layer buried at 200 m depth (Fig. 4D) and (B) a 1600-m diameter projectile impacting at 10 km/s into a target with a 400 m thick ice layer buried at 800 m depth (Fig. 8E).

Chapter 1b- Research on Martin terrain conditions

How are they formed? 3 Types of polygons and Case Studies

Totally covering more than one quarter of the planet. The extend of massive polygonal pattern.

- Desiccation cracks can act as an important indicator of the past presence of a water body or lake.

- Thermal contraction polygons form when an ice-cemented soil undergoes seasonal contraction resulting in high tensile stresses, which when large enough, can overcome the tensile strength of the soil, thus creating a network of fractures to relieve the stress. Repeated opening and closing of these fractures every season may lead to filling of these cracks with materials such as dust and loose sand to form sand-wedges (Mellon et al. 2008). In the case where liquid water occurs in shallow surface thaw zones, ice wedges can form by percolation into the open cracks. In either case, repeated seasonal cycles further widen the wedges and develop a distinct surface signature.

- At high altitude- there's more thermal cracking

- At lower latitude- less thermal cracking

- The sizes could range from 2-3m all the way up to 10km polygon shape

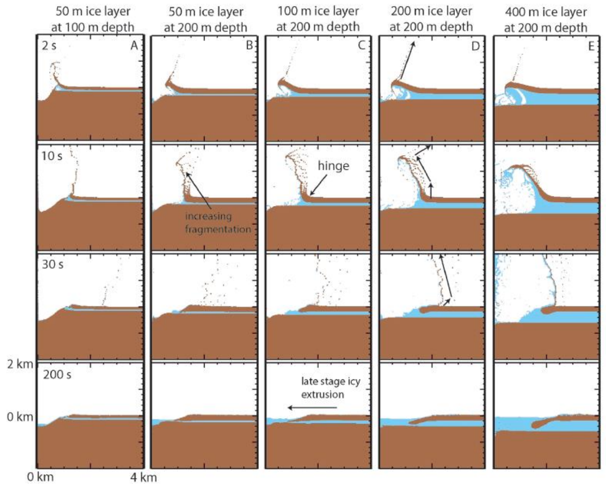


Fig. 4. 200-meter diameter projectile impacting at 10 km/s for different target configurations with a buried ice layer under Martian gravity. Dark color represents basalt and light color represents ice. Time increases downwards and the scale is the same in all panels. Arrows in column D show the ejecta blanket angles.

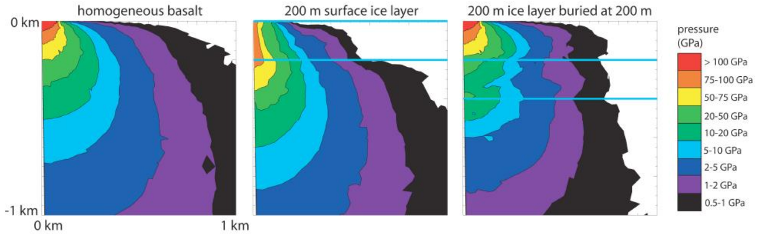


Fig. 5. Peak shock pressures as a function of initial position for a 200 m diameter projectile impacting at 10 km/s into different target configurations under Martian gravity. Horizontal lines show the initial location of ice layers.

Chapter 1c- Research on Martin terrain conditions

How are they formed? 3 Types of polygons and Case Studies

This research looks into the size of polygons of interest, thermal contraction, desiccation, volcanic and tectonic processes.

SMALL
- thermal contraction in forming small scale polygons on mars. Thermal stress builds up in the near surface at high latitudes to high enough values to cause fracture.

MEDIUM
- 15 to 350 meters in diameter.

LARGE
- Vary and may explain km-sized polygons located in the northern plains of Mars. Faulting and rebound of sediment fill in basin after removal of water/ iceload---- contributed to the giant polygons in utopia. (3-10km size)

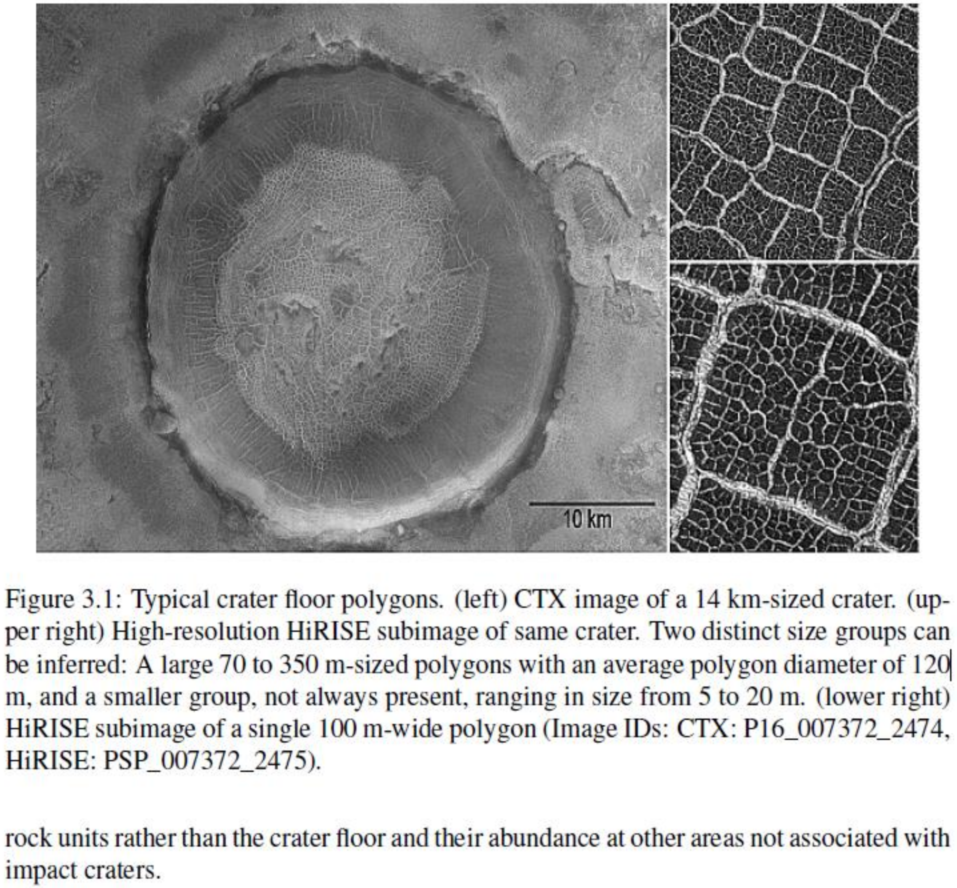


Figure 3.1: Typical crater floor polygons. (left) CTX image of a 14 km-sized crater. (upper right) High-resolution HiRISE subimage of same crater. Two distinct size groups can be inferred: A large 70 to 350 m-sized polygons with an average polygon diameter of 120 m, and a smaller group, not always present, ranging in size from 5 to 20 m. (lower right) HiRISE subimage of a single 100 m-wide polygon (Image IDs: CTX: P16_007372_2474, HiRISE: PSP_007372_2475).

rock units rather than the crater floor and their abundance at other areas not associated with impact craters.

Chapter 1d- Research on Martin terrain conditions

Drainage and Channel Incision

Mars have geomorphic characteristics that are inconsistent with prolonged erosion by surface runoff.

- Valley networks and channels on mars were discovered during the Mariner 9 mission in 1973.

- When the contribution of surface runoff and groundwater sapping to carving the valley networks and channels on Mar

Reason for looking into this is- how to control the stream and valley for stable foundation

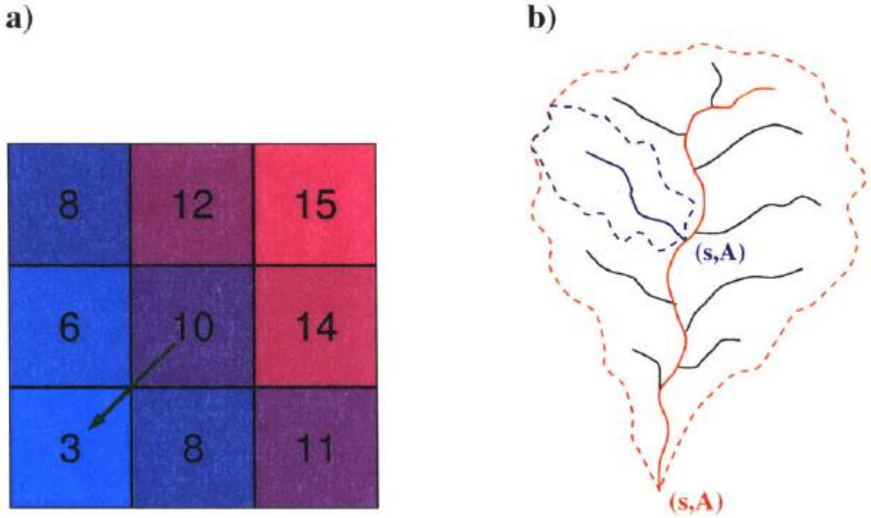


Figure 4-1: Watershed calculation. Panel a) is represents 9 grid cells for which the center cell drains in the steepest gradient direction, that is the lower left cell. Once flow directions are assigned, a local slope, contributing basin, and its area can be associated with each point, as shown in panel b).

Chapter 1e- Research on Martin terrain conditions

Drainage and Channel Incision Case Study on Earth : Colorado Plateau

Similar results are obtained for other fluvial systems on Mars, such as Naedi Vallis and canyons on the south walls of Valles Marineris.

STILL NEEDS RESEARCHING: how did they control the stream bed?

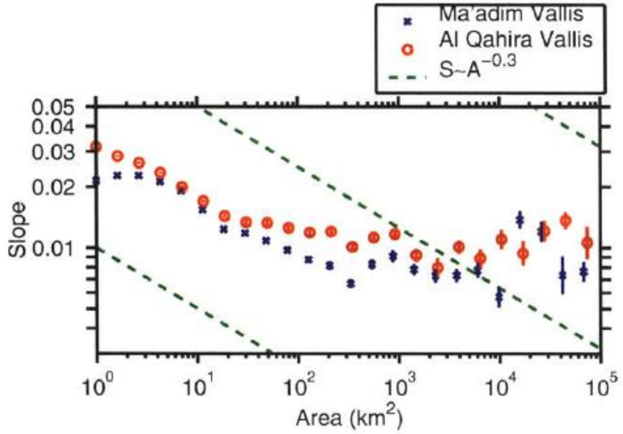


Figure 4-6: Slope-area relations for Ma'adim (crosses) and Al-Qahira (circles) Valles. Vertical bars indicate the standard errors in the mean slope. Also shown are reference lines (dashed) with concavity exponent $\theta = 0.3$. Since local slope falls off with area more slowly than in known fluvially eroded basins, we deduce that erosion by surface runoff was limited in these areas on Mars.

Chapter 2a- Introduction to Nordic Permafrost and Terrain

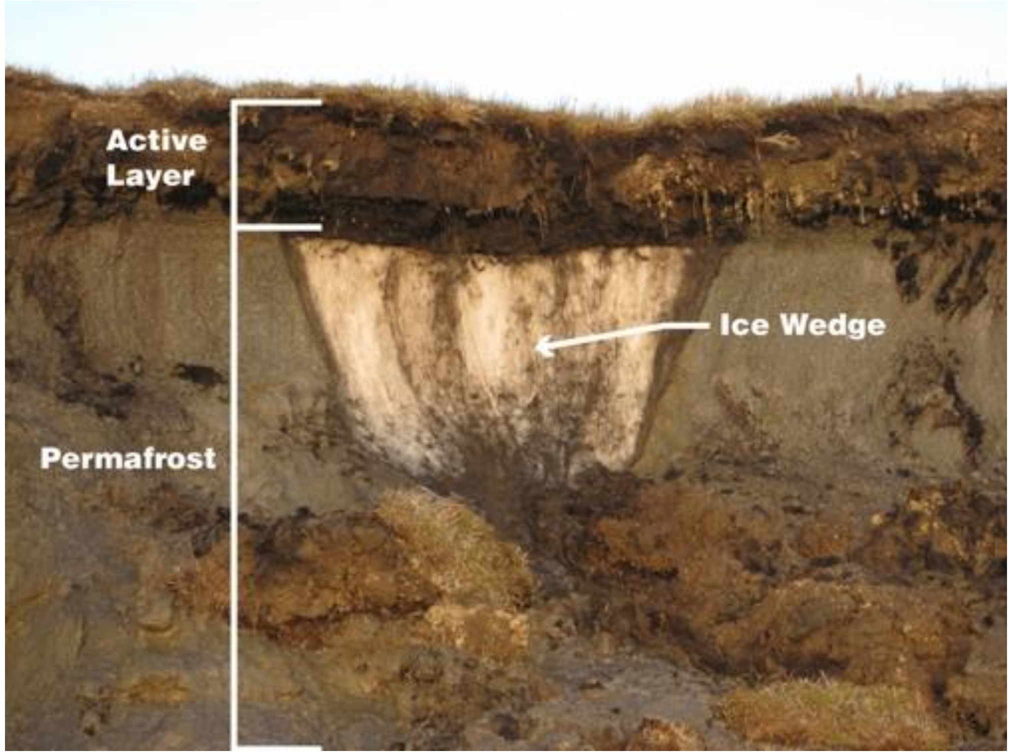
What is Permafrost- Nordic and Alaska based research

Initial Research:

- Permafrost is any ground (includes soil or underwater sediment which remains completely frozen- 0 degrees or colder for at least two years straight. These architectures are common in the north or south poles.
- Permafrost is made of a combination of soil, rocks and sand that are held together by ice. Lower Permafrost layers contain soils made mostly of minerals.
- A layer of soil on the top of permafrost is not always frozen all year. This is called the active layer. During summer, it thaws but during winter it freezes again.

Problem:

- Weakness with Permafrost architecture and shallow construction have many dangerous aspects due to thaw during summer and the climate impact. Estimated suggested nearly 70% of such infrastructure is at risk by 2050.



Chapter 2b- Introduction to Nordic Permafrost and Terrain

Comparing Martian environment with Nordic Permafrost

WHY IS COMPARING MARTIAN ENVIRONMENT WITH NORDIC PERMAFROST FOUNDATION IMPORTANT?

Due to global warming, the rate of permafrost thawing is accelerating. As air temperature in the arctic increases, ground temperature rises, resulting in thawing of the permafrost nearest to the ground surface, causing severe damages of the built infrastructure.

On Mars, there is also seasonal changes and day and night changes 3D printing seems to be a promising technique to build complex structures without the need of formwork and significant human intervention.

Chapter 3a- Introduction to Nordic Permafrost and Terrain

Requirements for any foundation chosen

File foundation design must meet requirements of:

1) The foundation must raise the building above the surface high enough to promote uninhibited air circulation beneath the building.

2) Heavy insulation must be placed on the floor of the structure so the heat loss through the bottom of the building is minimized.

3) Active layer, the ad freeze bond must be eliminated or reduced between the supporting piling, posts, or pier

4) The pile must be stabilized against lateral loads to safely withstand wind and or earthquakes

Chapter 3b- Historical Permafrost and Shallow Foundation

Slurred Piles

Slurred piles
- Predrilling is required and freeze back time is required to fully freeze the slurry before loading can be applied. Freeze back time depends on the amount of slurry that must be frozen. (Figure 1a) When slurred piles is in place, the portion of the pile in the active layer is typically wrapped with 3 layer of polyethylene. (most commonly used)

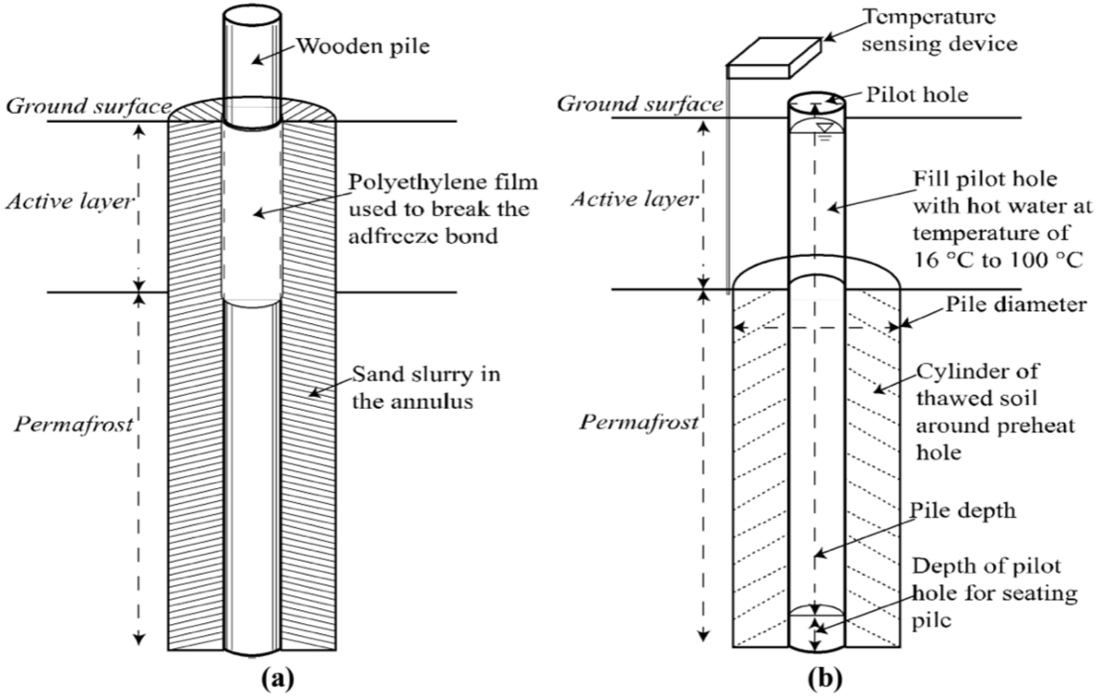


Figure 1. Typical deep foundations in permafrost regions (modified after McFadden, 2000): (a) typical slurried pile installation in permafrost; (b) preparation of pilot hole in preparation for driving a pile into permafrost

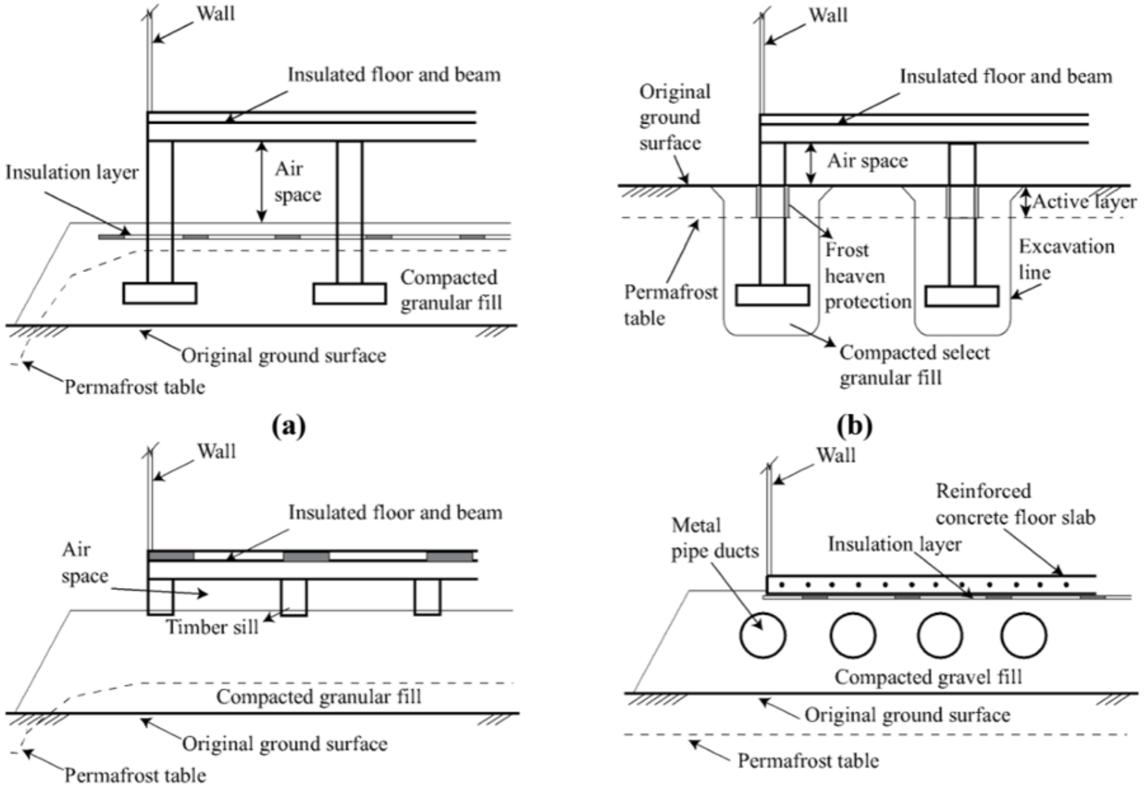
Chapter 3c- Introduction to Nordic Permafrost and Terrain

Drive Pile Support

Driven Piles support-
Driven into frozen soil without pre-treating the permafrost. The ice and frozen soil are viscoplastic materials, so the loaded pile will gradually settle as the ice in the ad freeze bond deforms.

The deformation of the ice in the ad freeze bond is called “creep”.
- Primary creep
- Secondarily creep
- Tertiary creep

Piles are elevated from the ground to prevent warming the frozen ground – allow cold air the refreee the active layer in winter.



Chapter 3c- Introduction to Nordic Permafrost and Terrain

Shallow Foundation Types

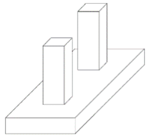


Figure 2-5: Combined Footing

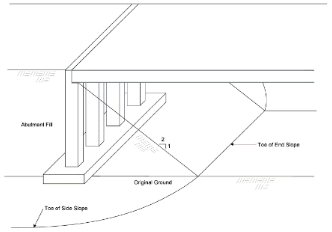


Figure 2-6: Spill-Through Abutment on Combination Strip Footing

1. Combination footing
are like isolated spread footings except that they support two or more columns and are rectangular or trapezoidal in shape (Figure 2-5). They are primarily used when the column spacing is non-uniform (Bowles, 1996) or when isolated spread footings become so closely spaced that a combination footing is simpler to form and construct.

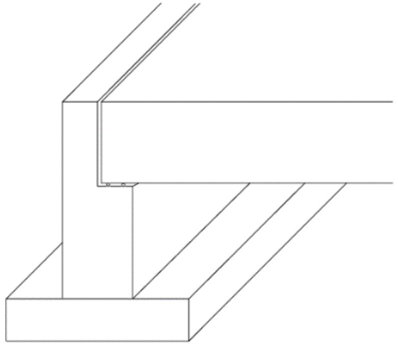


Figure 2-3: Spread Footing with Cantilever Stemwall at Bridge Abutment

2. Bridge abutments
Bridge abutments are required to perform numerous functions, including the following: • Retain the earthen backfill behind the abutment • Support the superstructure and distribute the loads to the bearing materials below the spread footing • Provide a transition to the approach fill

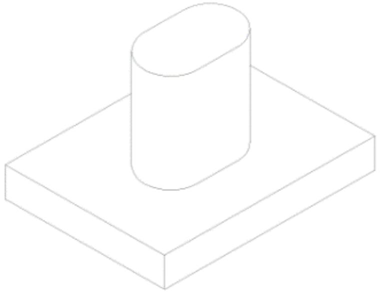


Figure 2-1: Isolated Spread Footing

3. Isolated Spread Footing
is the footing provided to support an individual column. Its design can be square, circular, or rectangular with a uniform thickness, and sometimes it's haunched or stepped for load distribution to the sides of the base. Pad footing is often designed to be a square plan area to make the reinforcing cage easier to construct and place

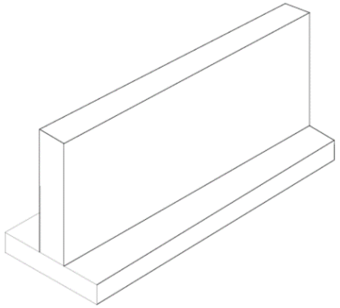


Figure 2-2: Continuous Strip Spread Footing

4. Continuous Strip Spread Footing

The most commonly used type of foundation for buildings is the continuous strip spread footing (Figure 2-2). Continuous or strip footings generally have a minimum length to width ratio of at least 5 (i.e., length > 5 x width). They support a single row of columns or a bearing wall to reduce the pressure on the bearing materials. These footings may tie columns together in one direction

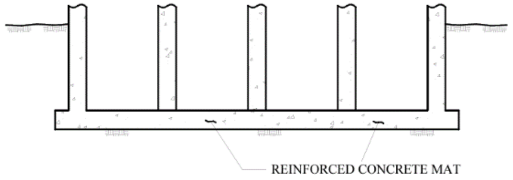


Figure 2-7: Typical Mat Foundation

5. Mat or raft footing

A Mat foundation is where a large slab is used to support several rows of parallel columns. mat or raft foundation is best used for heavy column loads. Because of its uniformity after its construction, mat foundation helps to reduce differential settlements on non-homogeneous soils or where there is variation in loads on the individual columns.

Chapter 3d- Introduction to Nordic Permafrost and Terrain

Types of ‘Slab-On-Grade’ Foundation

Typical shallow foundations used in permafrost regions (redrawn after Johnston, 1981):

(a) typical shallow foundation footing in permafrost, embedded in a thick, insulated gravel pad placed on the ground surface\

(b) typical shallow foundation footing in permafrost, placed in backfilled pit excavated below the original ground surface

(a) Shallow foundation on permafrost with typical timber sill surface foundation

(a) shallow foundation on permafrost with typical insulated concrete floor slab placed on duct-ventilated compacted fill

Discuss more in Chapter 7

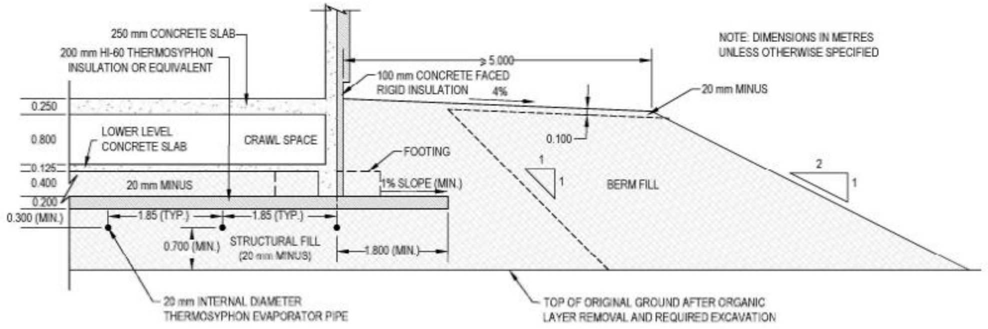


Figure 2 Recommended design section for a thermosyphon-stabilized building foundation

CASE STUDY: New Studio Building in Iqaluit, Nunavut.

Chapter 4a: What technology is needed to prevent thaw during seasonal changes

Analyze of Modern Case study

WHAT IS NEEDED FOR A HEATED STRUCTURE?
A heated structure – founded on permafrost is typically constructed on insulated and refrigerated granular fill pad--- to preserve the native permafrost

!) Rigid insulation – to reduce the heat transfer through the floor of the building to the permafrost foundation soils;

2) Foundation cooling system – to remove the heat from the foundation; the system includes a series of cooling devices that extract heat from the ground beneath the insulation; and

3) Structural fill pad – to support the structure and footings, serve as bedding for the cooling devices, and provide a thermal buffer zone to accommodate any seasonal thaw into the foundation when the cooling system is not in operation.

Chapter 4b: What technology is needed to prevent thaw during seasonal changes

Case study of: Thermosyphon system – New Studio Building in Iqaluit Nunavut

Thermosyphon system

A thermosyphon is a passive heat transfer device that operates by convection through vaporization and condensation. It consists of a sealed vessel with an upper part working as a condenser and a buried part in the ground functioning as an evaporator. Heat transfer is driven by the temperature difference across the unit.

Thermosyphons remove heat from the ground beneath a structure and release it to the outside ambient air, as long as the air is colder than the ground.

Thermosyphon technology and its use in foundation designs were presented in Hayley (1982), Haynes and Zarling (1988), Jardine et al. (1992), and Yarmak and Long (2002).

Case study- building foot print of 640m2

Foundation type is slab on grade with insulation and thermosyphons- to limit the thaw beneath the building

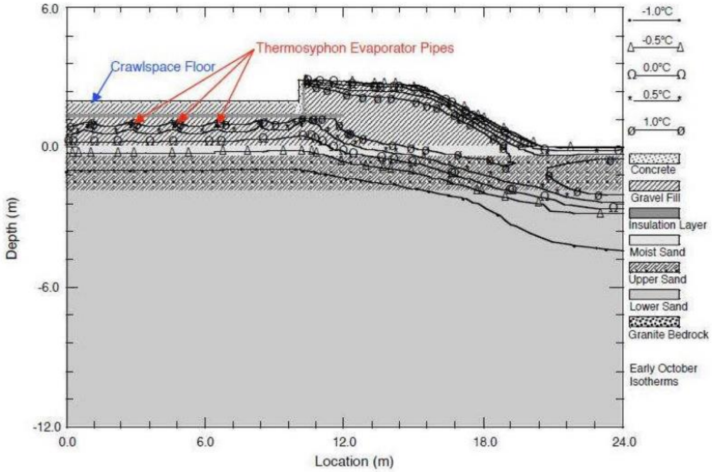


Figure 1 Estimated ground temperature distribution after thirty years of global warming for a section with a crawlspace for the building foundation

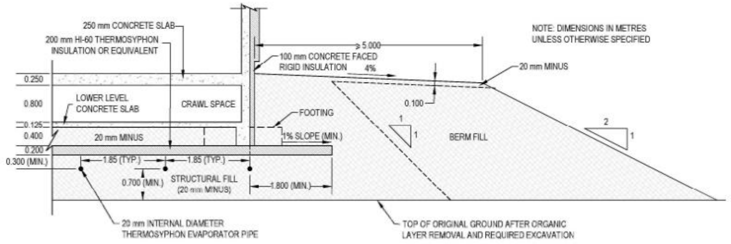


Figure 2 Recommended design section for a thermosyphon-stabilized building foundation

Chapter 4c: What technology is needed to prevent thaw during seasonal changes

Case study of: Process Plant in Northern Russia

Ventilated Duct System

Ventilated duct system: A series of parallel ducts buried in the foundation to allow cold air flowing through the ducts to cool the foundation during the warm period

when ambient air temperature is colder than the foundation; there are two types of the system: 1) passive natural convection and 2) active forced-air convection. Ventilated duct system and its use in foundation designs were presented in Nixon (1978), Odom (1983), Smith et al. (1991), and McKenna and Bigger (1998)

Case study- building footprint 75m wide and 200m length

Temperature is -4 to -5 degree t depth below 15m from the ground surface.

Ventilation duct system was selected as foundation colling system to control thaw stable bedding.

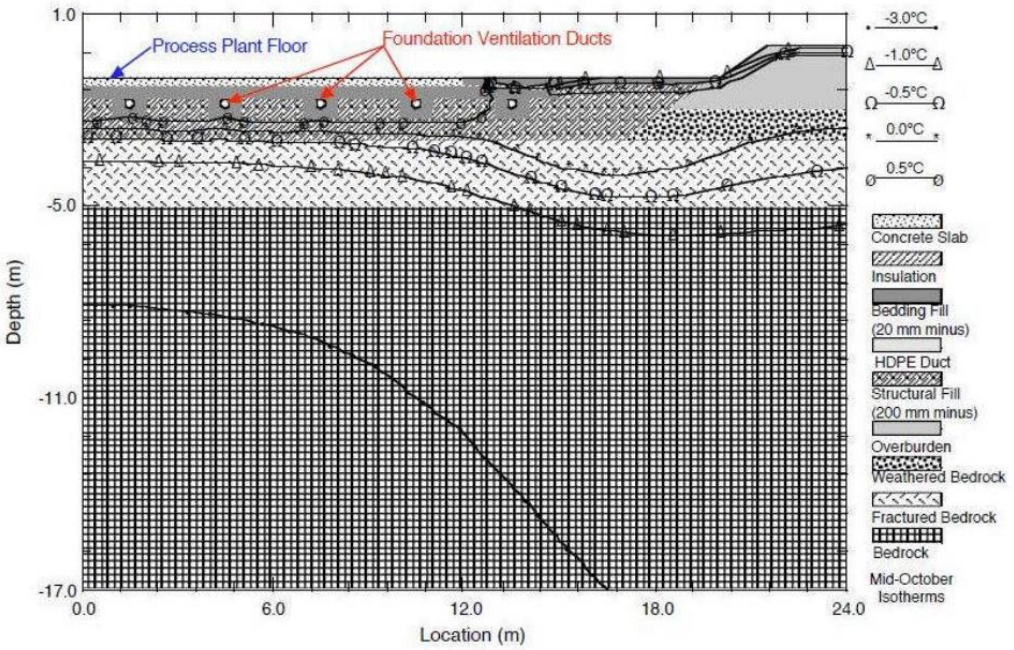


Figure 3 Estimated isotherms in the process plant foundation with a ventilated duct system

Chapter 4d: What technology is needed to prevent thaw during seasonal changes

Case study of: Ross River Yukon

Heat Pump system

Heat pump cooling system: Horizontal cooling pipe loops connecting to a heat pump in the building; the system includes a series of active refrigeration pipes that extract heat from the ground beneath the heated structure and dissipate the heat to the building for heating or release to the outside atmosphere when required. Goodrich and Plunkett (1990) presented cases using heap pumped cooling systems for building foundations over permafrost.

Case study- building foot print of 502m2

Foundation type will be slab- on – grade with heat pump chilled foundation system to promote permafrost preservation and limit the thaw beneath the building.

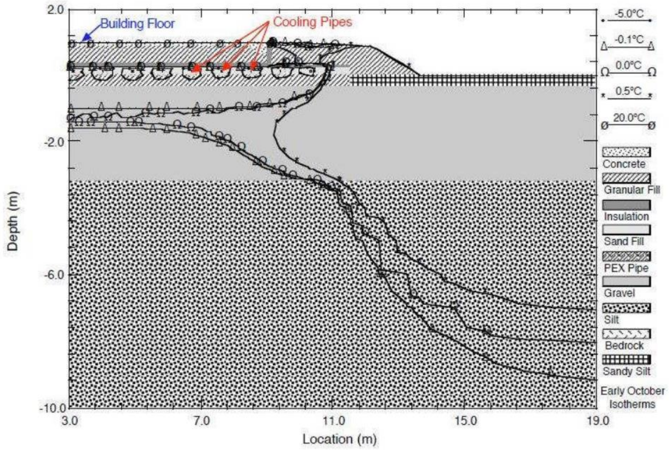


Figure 4 Estimated ground temperature isotherms after thirty years of building operation

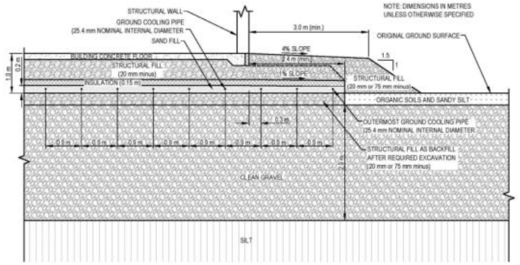
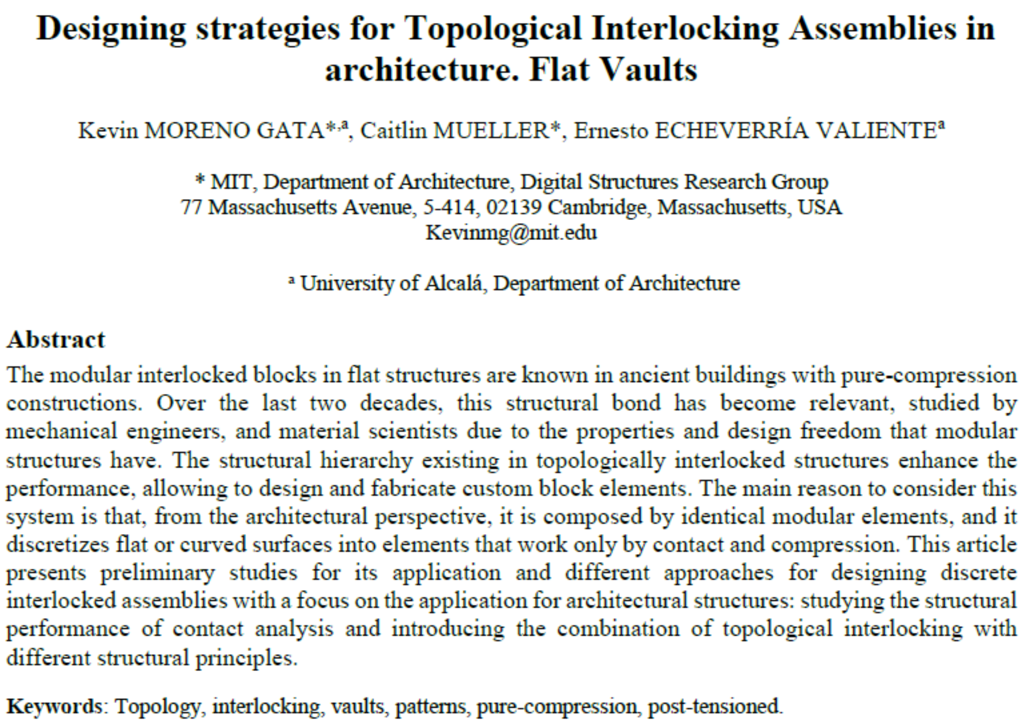


Figure 5 Recommended typical design section for a heat pumping chilled building foundation

Cooling fluid temperature will rise as heat is released from the ground through the ground cooling pipe walls into the fluid. The change in fluid temperature depends on the rate of heat released from the ground, the volumetric heat capacity of the fluid

Chapter 7a: Interlocking Voronoi Literature Reviews

Designing Strategies for Topological Interlocking Assemblies in Architecture. Flat Vaults.



Designing strategies for Topological Interlocking Assemblies in architecture. Flat Vaults

Kevin MORENO GATA*[a], Caitlin MUELLER*, Ernesto ECHEVERRÍA VALIENTE[a]

* MIT, Department of Architecture, Digital Structures Research Group
77 Massachusetts Avenue, 5-414, 02139 Cambridge, Massachusetts, USA
Kevinmg@mit.edu

[a] University of Alcalá, Department of Architecture

Abstract

The modular interlocked blocks in flat structures are known in ancient buildings with pure-compression constructions. Over the last two decades, this structural bond has become relevant, studied by mechanical engineers, and material scientists due to the properties and design freedom that modular structures have. The structural hierarchy existing in topologically interlocked structures enhance the performance, allowing to design and fabricate custom block elements. The main reason to consider this system is that, from the architectural perspective, it is composed by identical modular elements, and it discretizes flat or curved surfaces into elements that work only by contact and compression. This article presents preliminary studies for its application and different approaches for designing discrete interlocked assemblies with a focus on the application for architectural structures: studying the structural performance of contact analysis and introducing the combination of topological interlocking with different structural principles.

Keywords: Topology, interlocking, vaults, patterns, pure-compression, post-tensioned.

Summary and key questions answered in the Paper:

- How molecular materials can be applied?
- The systematization: possible alternatives as tensioned perimeters and post tensioning
- The study of geometric pattern alternatives.

Figure 1: Interlocked vaults examples (from left to right): Monastery of Escorial (1565), Cádiz Cathedral's Crypt (1730), Lugo's Cathedral (1699), Pontón de la Oliva (1853)

Historical Forms

From traditional architectural perspective, the flat vaults discretize horizontal surfaces into elements that work only in pure compression. Likewise, the masonry vaults, transmitting the load not directly by its shape but by its contact elements geometry.

Stereotomy: **Abeille's Bond** with Mathematician Truchet and engineer Frieze- they introduced a non-orthogonally (hexagonally patter to transmit the force, showing it exists certain flexibility in building interlocking structures.

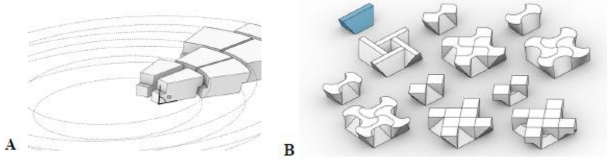


Figure 2: Patterns comparison: (A) Circular vault of Escorial, (B) (blue) *Abeille's Vault*, and *Truchet* and *Freizer* topologies alternatives.

Reinterpretation of Abeille's Vault Logic

This modular example has the flexibility of a lightweight structure, later stiffened with infill material. Shell could be manufacturer through forming rigid panels.

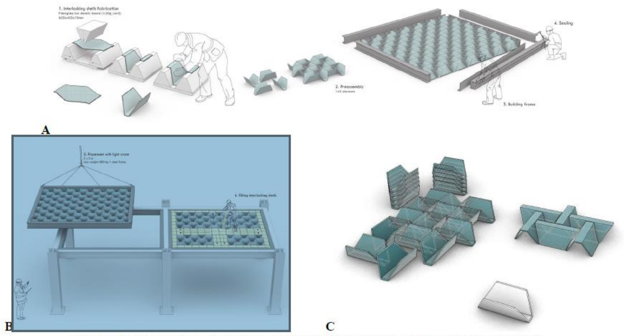


Figure 12: Interlocking shell slab. Assembly. Interlocking shells as lost form-work.

During this test, the goal was to reducing their volume and weight, but making them stronger. While reducing its geometry, the contact surface is reduced from the original. Create more significant contact stress in less area, being necessary to reinforce the block.

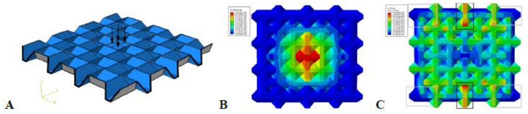


Figure 13: FEA analysis. (13c) Displacement (13d) Stress von Mises.

Chapter 7b: Interlocking Voronoi Literature Reviews

Design of architecture materials based on topological and geometrical interlocking

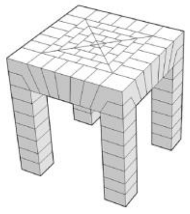
Abstract
This paper investigates the principles that regulate complex stereotomic constructions as a starting point for the design of a new two-dimensional floor structure based on the principles of TIM (Topological Interlocking Materials). These interlocking systems use an assembly of identical Platonic solids which, due to the mutual bearing between adjacent units and the presence of a global peripheral constraint, lock together to form pure geometric shapes. This type of structure offers several advantages such as a high energy dissipation capacity and tolerance towards localised failure, which has made it a popular research topic over the last 30 years. The current research project includes a case study of an assembly of interlocking cubes to create a "flat vault". The resulting vault design features a striking appearance and its geometry may be manipulated to achieve different two-dimensional solutions, provided certain geometric conditions necessary for the stability of the system are followed.

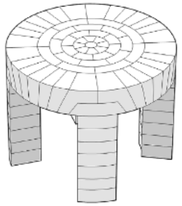
Keywords Stereotomy · Flat vault · Topological Interlocking Materials (TIM) · Interlocking Platonic solids · Floor surfaces

Topological Interlocking Materials

Interlocking systems use an assembly of identical platonic solids.

- Can withstand concentrated loads without loosing its structural integrity.
- Advantages of high energy dissipation capacity and tolerance towards localized failure.
- Using interlocking cubes to create **flat vault**., to create a structure held together by a peripheral constraint or rings beam.





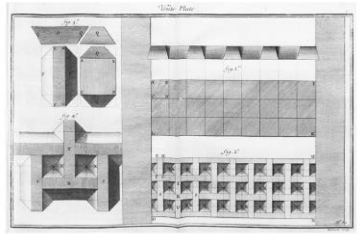


Fig. 3 Joseph Abeille's "Voûte plate": drawings of polyhedral stone modules and assembled system of a flat vault, invented in 1699. Image: Gallon (1735)

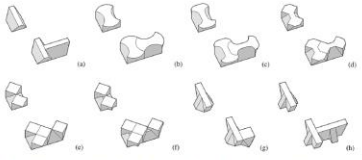


Fig. 4 Alternative geometric modules for Abeille's vault: **a** Abeille's module; **b** Truchet's module; **c–h** Frézier's modules. Images: Francesca Lecci

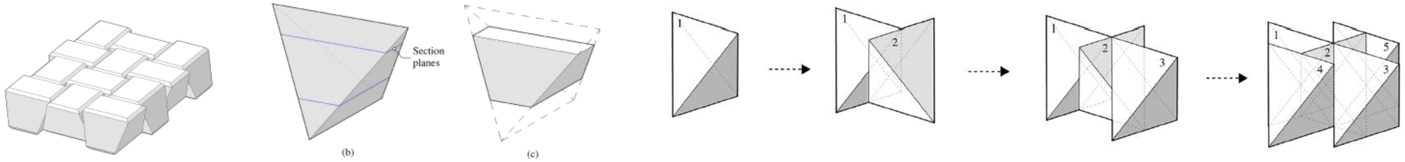
Historical Precedents

Common Vault vaults can be geometrically generated as a result of the longitudinal extrusion of a jack arch. Commonly used at the end of Gothic Period and Cathedral in Seville.

Abeille's structure- to create a flat, walkable extrados for the vault.

Topological Interlocking Materials (TIM)

First assembly of Polyhedral is **Michael Glickman's** invention of **the G-Block system**. First modern structure using **Interlocking Truncated Tetrahedra**



a Interlocking principle of the G-Block system; **b** Platonic solid composed of four equilateral triangular faces ; **c** the G-Block solid within the tetrahedron; d Sequential assembly of unit elements to create topologically interlocking tetrahedra.

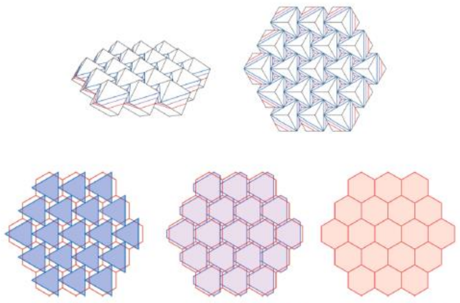


Fig. 9 Analysis of the progressive evolution of the section of the TIM interlocking system, consisting of cubes, along the direction perpendicular to the plane containing the flat vault. Image: Cecilia Mazzoli

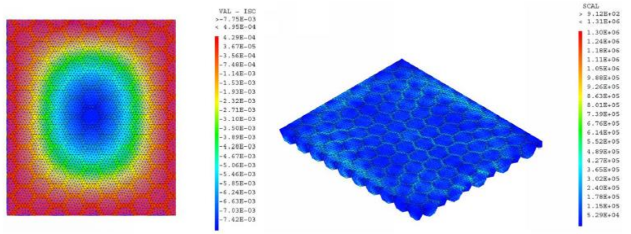


Fig. 15 Left: vertical displacement of the ashlars in metres (view from top). Right: Von Mises stress distribution within the ashlars (axonometric view) in Pa. Image: Lecci (2013)

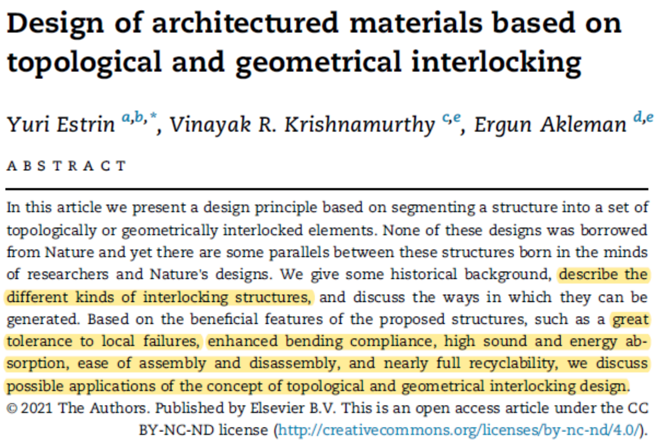
Flat Vault Composed of Interlocking Cubes & Load Analysis

A section through a cube at an include plane, passing through its center and the midpoints of its edges, obtain a regular hexagonal section.

This allows free rotation. When exerting suitable pressure, the vertical displacement of the structure are shown.

Chapter 7c: Interlocking Voronoi Literature Reviews

Design of architecture materials based on topological and geometrical interlocking



Design of architectured materials based on topological and geometrical interlocking

Yuri Estrin [a,b,*], *Vinayak R. Krishnamurthy* [c,e], *Ergun Akleman* [d,e]

ABSTRACT

In this article we present a design principle based on segmenting a structure into a set of topologically or geometrically interlocked elements. None of these designs was borrowed from Nature and yet there are some parallels between these structures born in the minds of researchers and Nature's designs. We give some historical background, describe the different kinds of interlocking structures, and discuss the ways in which they can be generated. Based on the beneficial features of the proposed structures, such as a great tolerance to local failures, enhanced bending compliance, high sound and energy absorption, ease of assembly and disassembly, and nearly full recyclability, we discuss possible applications of the concept of topological and geometrical interlocking design.

1) We start by describing the topological interlocking structures built **from convex polyhedral (Platonic bodies)**

2**) Topologically interlockable blocks** with concavo-convex contact surfaces, which can be assembled to planar or curved layers – **Ostemorphic blocks**

3)**Bio-inspired topological linterlocking** Structures segmented into topologically interlockable space-filling blocks referred to as **Delaunay lofts** and generalized **Abeille Tiles**

4) biomimetics concept- space filling structures based on geometrically **interlocked fabric weaves** as blueprints

5) Finally, in Section 3 we shall discuss the mechanical properties of topological interlocking assemblies that have already been manufactured and tested.

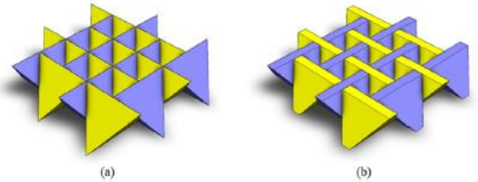


Fig. 2 – Assembly of topologically interlocked tetrahedra: (a) full tetrahedra, (b) truncated tetrahedra. The different colors suggest that blocks made from different materials can be integrated within an assembly.

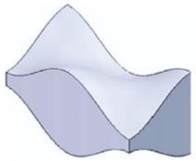


Fig. 7 – Modified geometry of the osteomorphic block, after [26].

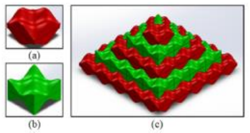
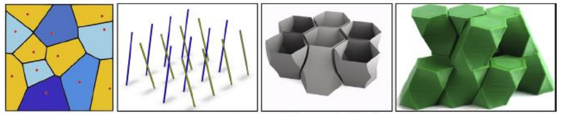
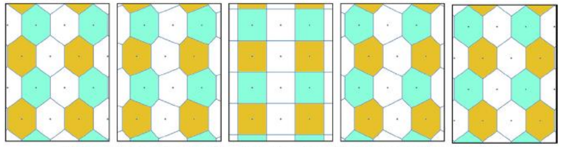


Fig. 8 – Osteomorphic-like blocks of different shapes ((a) and (b)) enabling a space-filling assembly (c) (Adapted from [26].).



(a) Voronoi tessellation of a set of sites (red)
(b) Line arrangement for Delaunay Lofts
(c) Delaunay Lofts after layer-wise Voronoi tessellation
(d) 3D printed assembly of Delaunay Lofts



(e) Voronoi tessellations for five selected layers used in Delaunay Loft construction.

1) Convex polyhedral (Platonic bodies)

Tetrahedron geometry of the elementary building block was considered.- became a prototype for further interlockable shapes based on convex polyhedral or their derivation notably all Platonic bodies

It was derived from historical examples- the Abeille Vault

A property crucial is- A tetrahedron obstruct its upward movement, while the other two prevent its downward movement.

2) Topological interlocking with Osteomorphic blocks

- Tilting of cylinder surfaces with modified Osteomorphic blocks- proposed by the matching of concavo- convex contact surfaces of the blocks.

3) Bioinspired topological interlocking – Delaunay Lofts and Generalized Abeille Tiles

Two specific examples of bioinspired topologically interlocking material design are Delaunay Lofts and Generalized Abeille Tiles.

Why Delaunay Lofts? It is the hyperbolic paraboloidal shape of their boundary- any two non-coplanar lines in 3D space separate the space along a hyperbolic paraboloidal surface, which by nature has a concavo- convex shape thereby leading to the possibility for interlocking.

Delaunay Loft example is the 'hex-quad-hex (6-4-6 configuration by Subramanian – interlock along one direction on the horizontal plane. 5-4-5 shape is bounded by hyperbolic paraboloidal shapes on all sides- completing topological interlocking in the plane.

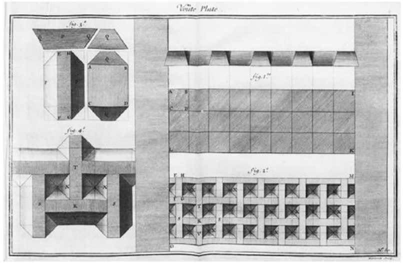


Fig. 3 – Topological interlocking in flat vaults. A sketch from J. Abeille's patent, after [15].

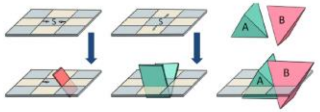
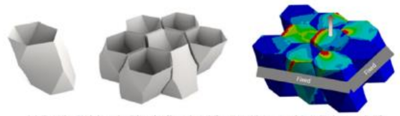
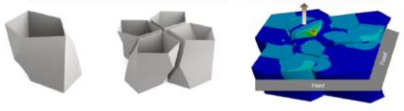


Fig. 4 – Algorithm for building a 3D structure of interlocked tetrahedra starting from a plane tessellated with squares.



(a) Topological interlocking is directional for 6-4-6 hex-quad-hex Delaunay Loft



(b) Topological interlocking is complete for 5-4-5 pent-quad-pent Delaunay Loft

Chapter 7c: Interlocking Voronoi Literature Reviews

Design of architecture materials based on topological and geometrical interlocking

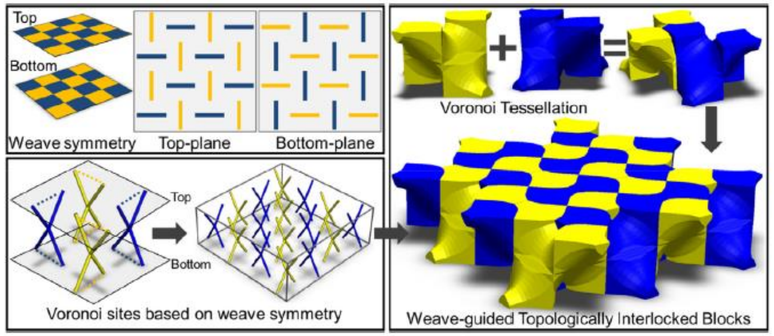
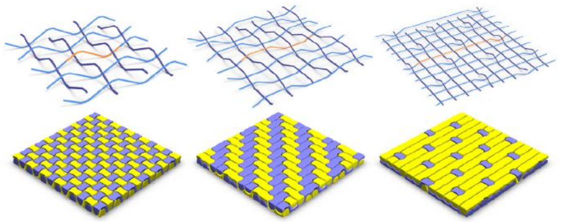


Fig. 11 – Generation of topologically interlocking structures guided by textile weave patterns.



(a) Plain Woven Tiles (b) Twill Woven Tiles (c) Satin Woven Tiles

Fig. 12 – Woven Tiles for three different types of weave patterns. The top row shows the Voronoi sites (curves) designed using fabric weaves and the bottom row shows the structures resulting from 3D Voronoi tessellations of the sites.

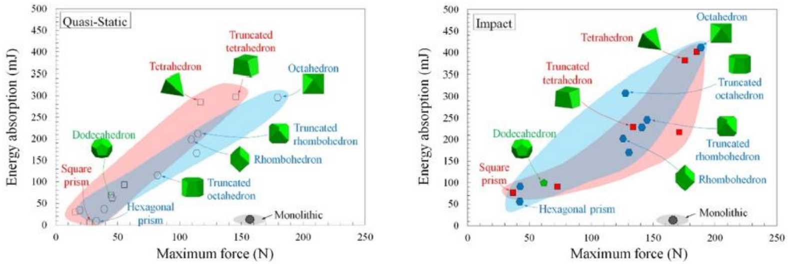


Fig. 15 – Mechanical response of different types of ceramic panels assembled from topologically interlocked blocks generated from full or truncated Platonic bodies under quasistatic (left) and dynamic (right) loading [54].

4) Geometrical Interlocking

- Notion of fabric weave
- Geometrical interlocking is a counterpart for topological interlocking that does not require tensioning forces to keep the assembly intact-
- It can not be assembled without deforming, breaking, cutting at least one pieces of the assembly
- If a geometrically interlocking assembly is somehow created in a pre-assembled fashion, then it can not be assembled without deforming.
- Woven Tiles utilizes the idea of 3D Voronoi tessellations in conjunction with fabric weave– to construct a space filling geometry- without leaving any voids- complete contact with all other elements.

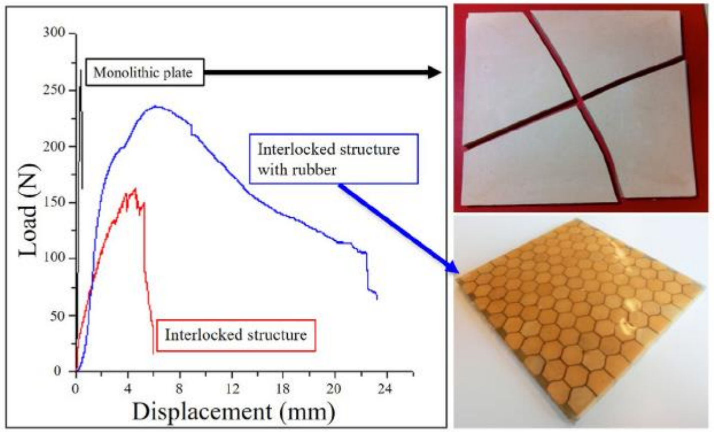
5) Results of Topological interlocking structures

- Since the blocks are not bonded together, a crack initiated in one of them and propagating towards its interface with an adjacent block gets blunted- this creates secondary cracks at block interfaces- leads to energy dissipation and fracture resistance.

- Topological interlocking structures exhibit a substantially enhanced toughness over monolithic counterparts.

- Topologically interlocking materials also possess an extraordinarily high sound absorption capability.

- Left hand side is a comparison of different polyhedral based blocks under maximum sustainable load and energy absorption of the panels



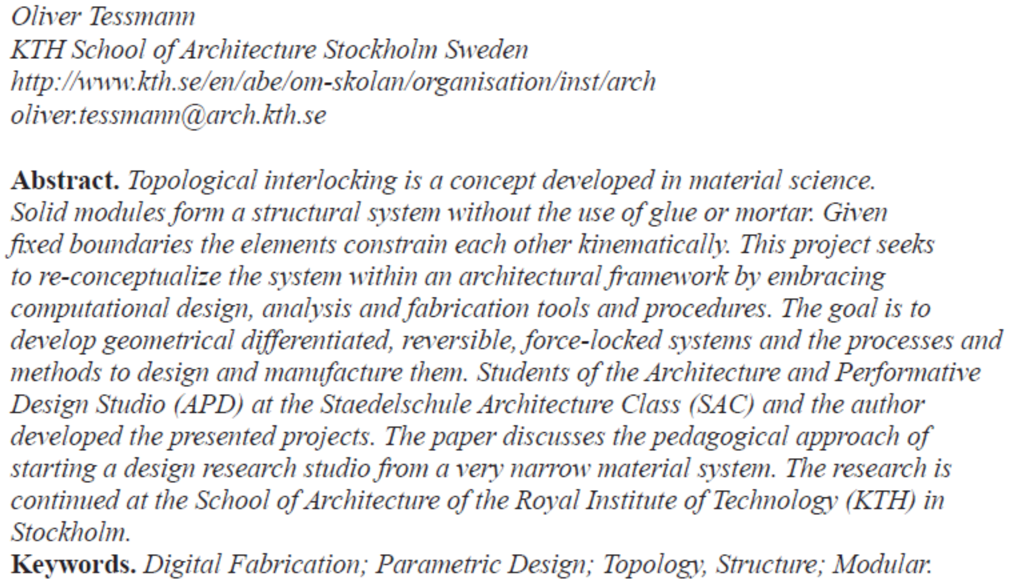
Effect of interleaving the blocks with soft rubber on the load-deflection curve for a planar assembly of Osteomorphic

5) Results of Topological interlocking structures

- The use for building temporary habitats in disaster areas is a further possibility- applications in extraterrestrial construction were considered in the EU funded Regolith project devoted to development of lunar habitat.
- As diagram shown above- testing 3D printed monolithic printed panels composed by hard interlocked Ostemorphic blocks interleaved with soft layers- plain and twill weaves admit a bi-directional distribution of stress (across both wrap and weft direction- exhibit a uni-directional distribution
- Look into Topological interlocking emerging research into the potential of gematrical interlocking includes the use of machine learning techniques to enlarge the design space by generating new structures and **predict their mechanical properties**

Chapter 7d: Interlocking Voronoi Literature

Topological Interlocking assemblies



Oliver Tessmann
KTH School of Architecture Stockholm Sweden
http://www.kth.se/en/abe/om-skolan/organisation/inst/arch
oliver.tessmann@arch.kth.se

Abstract. *Topological interlocking is a concept developed in material science. Solid modules form a structural system without the use of glue or mortar. Given fixed boundaries the elements constrain each other kinematically. This project seeks to re-conceptualize the system within an architectural framework by embracing computational design, analysis and fabrication tools and procedures. The goal is to develop geometrical differentiated, reversible, force-locked systems and the processes and methods to design and manufacture them. Students of the Architecture and Performative Design Studio (APD) at the Staedelschule Architecture Class (SAC) and the author developed the presented projects. The paper discusses the pedagogical approach of starting a design research studio from a very narrow material system. The research is continued at the School of Architecture of the Royal Institute of Technology (KTH) in Stockholm.*

Keywords. *Digital Fabrication; Parametric Design; Topology, Structure; Modular.*

Summary and key questions answered in the Paper:

- How are these topological interlocking assemblies derived from vernacular arcs, vaults, shells, brickwork structures and masonry?
- Planar assemblies of solid and repetitive polyhedrons and Osteomorphic blocks- capable of resisting external loads impacting perpendicular to the main load bearing direction due to force locked interfaces between their elements0 able to resist high bending forces and even tension without binding materials like mortar.
- Chanachai's windmill like modules
- Delkash's faceted tetrahedrons and the tubular configuration
- Topological interlocking assemblies- tolerate deformation and seismic loads while maintaining structural capacity. Are load bearing and can be disassembled. Used for both micro particles to large scale coastal barrier modules.

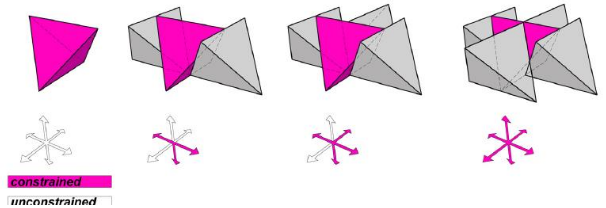
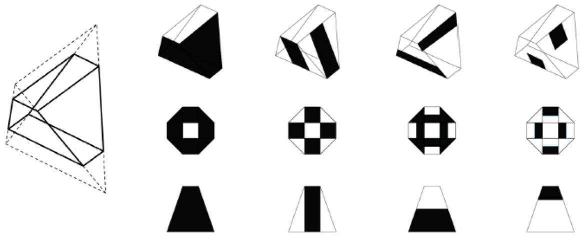
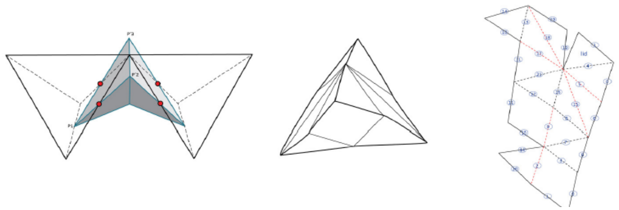
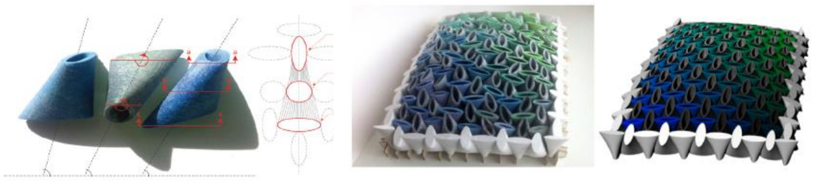


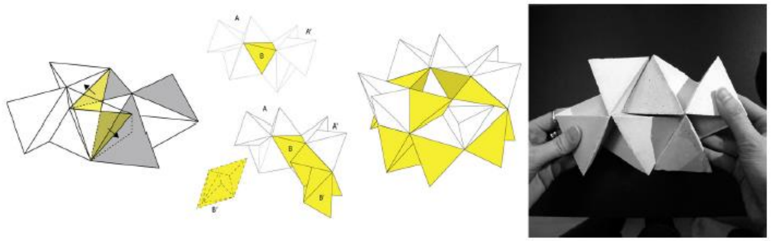
Figure 1
Tetrahedron configuration with interlocking properties. From left to right the middle tetrahedron is increasingly constrained in all directions by its neighbours.

Figure 2
Left: The tetrahedron is cropped to eliminate sharp edges which are difficult to cast and vulnerable in construction. Right: Study on the variation of contact zones between the modules. Areas marked in black establish an interlocking zone with the neighbouring module. Altering size and location of these zones changes the porosity of the system the topological interlocking is unaffected (Image: Philipp Mecke).









TopoStruct

- Less interested in minimizing material use- more interested about the differentiation of modules and their material properties from load bearing to moistening or light transmitting driven by a generative digital model.

Increase Geometrical Repertoire of Topological Interlocking Assemblies

-Phillipp Mecke- initial assembly of tetrahedrons, repetitive in size and geometry, forms a closed plane.

Ňasim Delkash develop module with 16 faces.

-16 faces. The shape is built up from 4 tetrahedron. The contact points are the red dots.

Increase the degree of Interlocking- Windmill like modules

-All system presented use one interfacing zone between two modules to constrain movement in one direction.

- This is used for retaining facilities against mud floods in Thailand's Khao Phanom region

Boarder Condition

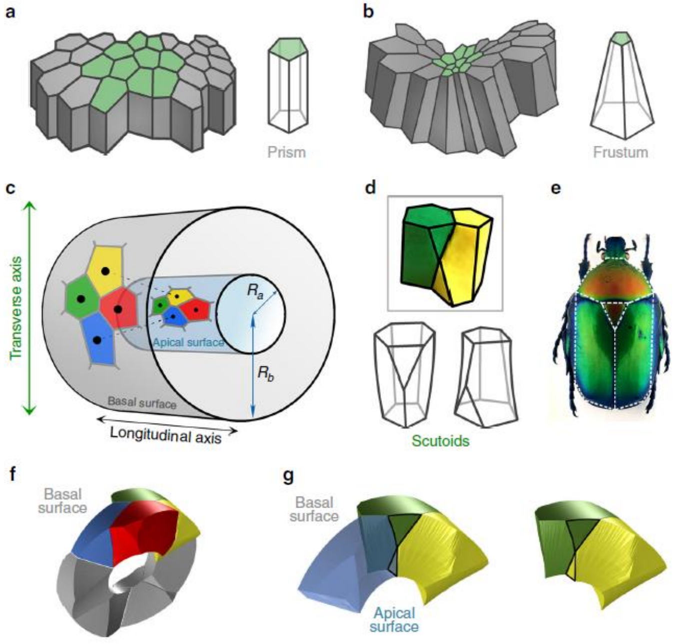
-Similar to Donlaporn Chanachai windmill shape modules. Two planes with different orientation are interfacing two windmills like Wmodules. Modules can be joined in more than one way. This allows for interlock assemblies without fixed boarders. Complex interlocking prevents thrust in the system

Chapter e: Interlocking Voronoi Literature Reviews

Scutoids are a geometrical solution to three-dimensional packing of epithelia

Abstract

As animals develop, tissue bending contributes to shape the organs into complex three-dimensional structures. However, the architecture and packing of curved epithelia remains largely unknown. Here we show by means of mathematical modelling that cells in bent epithelia can undergo intercalations along the apico-basal axis. This phenomenon forces cells to have different neighbours in their basal and apical surfaces. As a consequence, epithelial cells adopt a novel shape that we term “scutoid”. The detailed analysis of diverse tissues confirms that generation of apico-basal intercalations between cells is a common feature during morphogenesis. Using biophysical arguments, we propose that scutoids make possible the minimization of the tissue energy and stabilize three-dimensional packing. Hence, we conclude that scutoids are one of nature's solutions to achieve epithelial bending. Our findings pave the way to understand the three-dimensional organization of epithelial organs.



A tubular model reveals apico-basal cell intercalations:

a) Investigate 3D packing in curved epithelia

b) Computed a cylindrical epithelium, mimic epithelial tubes and glands.

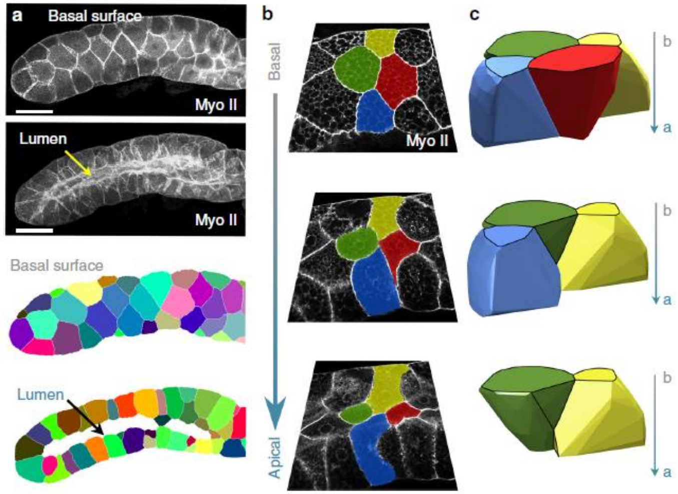
c) The ratio between the outer cylinder radius and the inner cylinder radius, determines how large the relative expansion of the basal surface is.

d) Voronoi diagram is generated by a set of seeds in space.

1. Generate a Voronoi diagram on the inner surface.
2. Generating a second Voronoi diagram in the basal surface of the tube.

Scutoids, in contrast to prisms/ frusta are not convex and present non-planar lateral faces. Boundary between cells follow geodesic trajectories– Scutoids display concave surfaces, allow 3D packing of cells in curved tissues.

Cells arrange around a lumen to form a cylinder.



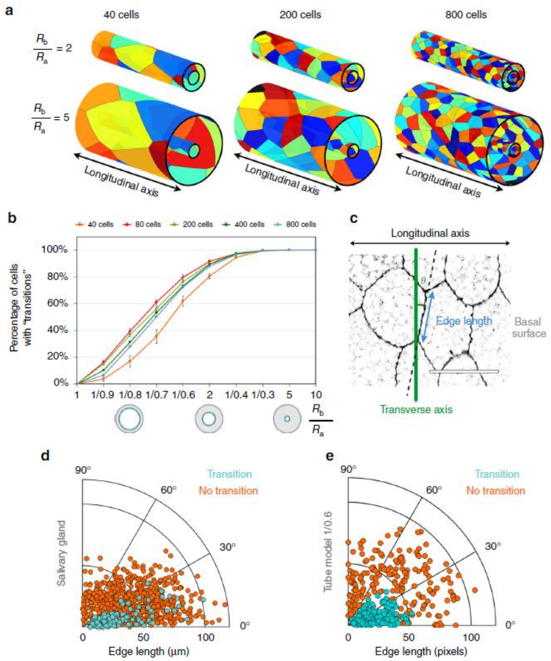
Scutoids appear in Tubular epithelia

3D tissues packing of curved epithelia

a) Example of salivary gland and it’s processed images.

b) Confocal images showing the apico basal cell interactions of epithelial cells marked with green, yellow, red and blue colors.

c) 3D reconstruction of the same cell- confirms the presence of concave surfaces.



A Line tension minimization framework to analyze 3D packing.

a) Example of 40, 200 and 800 cells models resulting from basal expansion of two and five times the apical surface.

b) Percentage of cells involved in transition Scutoids in relation to the increase the surface ratio.

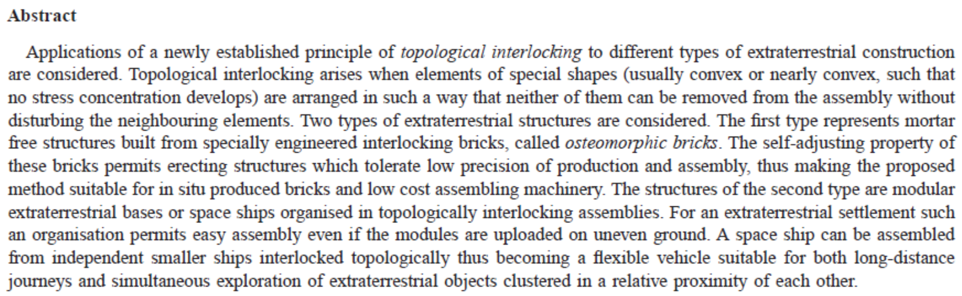
c) Scheme demonstrates how are measured the edge angle with respect the transverse axis and the edge length in a four cells motif.

d) Polar scatter showing the length and the angle of contacting edge

e) Polar scatter

Chapter f: Interlocking Voronoi Literature Reviews

The Principle of Topological interlocking in extraterrestrial condition



Abstract

Applications of a newly established principle of *topological interlocking* to different types of extraterrestrial construction are considered. Topological interlocking arises when elements of special shapes (usually convex or nearly convex, such that no stress concentration develops) are arranged in such a way that neither of them can be removed from the assembly without disturbing the neighbouring elements. Two types of extraterrestrial structures are considered. The first type represents mortar free structures built from specially engineered interlocking bricks, called *osteomorphic bricks*. The self-adjusting property of these bricks permits erecting structures which tolerate low precision of production and assembly, thus making the proposed method suitable for in situ produced bricks and low cost assembling machinery. The structures of the second type are modular extraterrestrial bases or space ships organised in topologically interlocking assemblies. For an extraterrestrial settlement such an organisation permits easy assembly even if the modules are uploaded on uneven ground. A space ship can be assembled from independent smaller ships interlocked topologically thus becoming a flexible vehicle suitable for both long-distance journeys and simultaneous exploration of extraterrestrial objects clustered in a relative proximity of each other.

The paper will consider two structures:

1) Osteomorphic bricks

The self adjusting property of these bricks permits erecting structures which tolerate low precision of production and assembly

2) Modular extraterrestrial bases or spaceships organized in topically interlocking assemblies.

For extraterrestrial settlement- a spaceship can be assembled from independent smaller ships interlocking topologically.

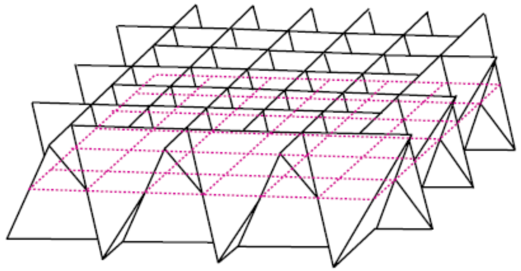


Fig. 3. A layer-like square-based structure of interlocked tetrahedra.

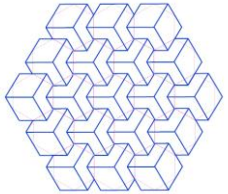


Fig. 4. A layer-like hexagon-based structure of interlocked cubes.

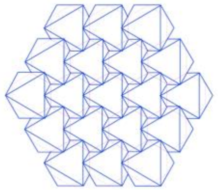


Fig. 5. A layer-like hexagon-based structure of interlocked octahedra.

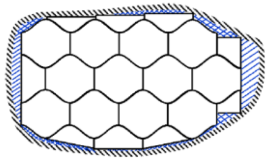


Fig. 6. Interlocking foundation built in a pit. The grey hatched area represents the pit wall; the upper and lower gaps between the walls and the structure (double-hatched) are filled with expanding grout. The other gaps may be left unfilled.

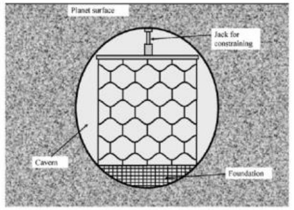


Fig. 7. Interlocking structure built in a cavern. The foundation can be built, e.g., from regolith.

Interlocked Tetrahedra

Con: Each tetrahedron has a pair of opposite faces inclined in one direction with the other pair inclined another direction- any attempt to remove the element from assembly results in pushing a couple neighboring elements in plane away from the element in question

If the movement of the neighboring elements is prevented, for instance by applying an in-plane compression or peripheral constraint, the tetrahedral element will be arrested within the structure

Osteomorphic blocks

Upward and downward movements of the element are prevented by different faces. Interlocking can be achieved through a single face of an element. Only requires unidirectional constraint preventing the separation of curved faces of the bricks.

In the Osteomorphic block, each curved surface prevents its displacement along the normal to the assembly in either direction.

Shape of interlocking surfaces, make the blocks self-adjusting- if inaccurate initial placement of block will lead to itself positioning into the correct place.- construction can be in-situ mass production

Constraints by the natural features of planetary topography: foundations and in-built cavern structures.

Fig 6 The upper and lower gaps between the interlocking assembly and the pit walls should be either filled with regolith

Fig 7 Utilizing the natural environment to provide constraint are in built structures in caverns or lava tubes. In this case, only gaps between the structure top and the cavern roof should be either filled with expanding grout or equipped with the pressuring jacks.

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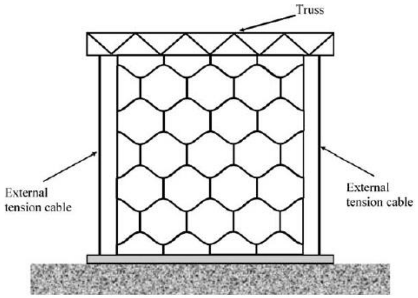

Fig. 8. An example of constraining by external frame.

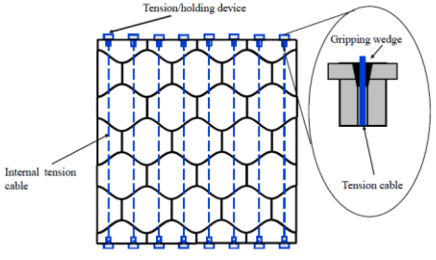

Fig. 9. Constraining by post-tensioning of internal cables.

Constraints by the natural features of planetary topography: foundations and in-built cavern structures.

Figure 8. require supply of pre-manufactured members and is not insitu.

Fig 9. internal tension cables running through bricks- cables will have to be tensioned, done through looping the cables around the structures.

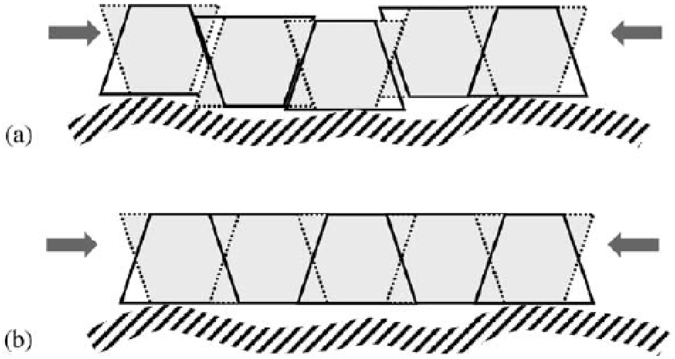

Fig. 13. Construction on uneven surface using the self-adjusting property of the interlocking modules. Here for illustrative purposes interlocking is indicated by two parallel sections: (a) initial positioning of the pre-fabricated modules uploaded on uneven ground; the arrows indicate the assembling force applied to the collection of modules and (b) the resultant assembly.

Self-adjusting modules for an extraterrestrial base

The advantage of using the interlocking organization of modules is in the inherent self-adjusting property of topological interlocking. The same geometry that locks the elements within the structure ensures that if in a loose structure the elements are not properly aligned, application of lateral load will force them into a regular planar arrangement

Fig. 13a sketches a collection of modules after they have been uploaded on an uneven ground. Then a lateral force needs to be applied to assemble them into a cohesive structure, Fig. 13b
Due to low gravity, does not require special ground preparation for instance in the shape of tetrahedra, cubes or octahedra)

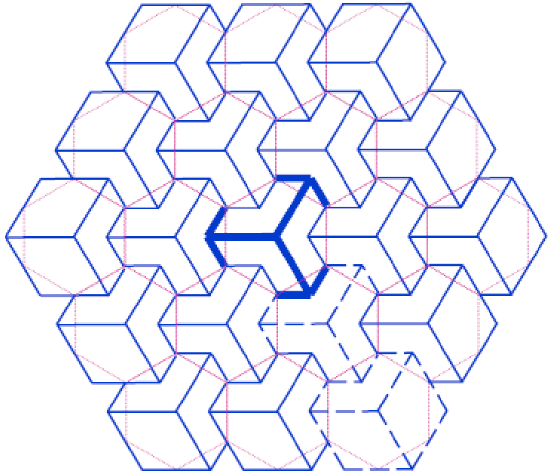

Fig. 14. A path to service a faulty module (highlighted): broken lines show the modules that should be removed to access the faulty module.

Removing of modules from the structure

For Osteomorphic blocks- can be tolerant to missing blocks

Hexagon tiling based structures do not tolerate missing blocks and disintegrate once a single block is removed or fails.

However, hexagonal tiling-based structures are easy to require, as each module can be accessed by removing modules one by one via the shortest route leading to it.