Deployable Interlocking Structures for Martian Bases

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Abstract. We propose a new construction system for a Martian base based on the hybrid blocks made of pre-fabricated and delivered shells filled *in-situ* with regolith. In order to avoid the difficulties with connecting the building blocks (as mortar being cured in low pressure conditions loses its strength), we propose to use the octahedron block geometry, which supports topological interlocking. Structures based on topological interlocking do not require binder to maintain their integrity. Furthermore, they have high fracture resistance and self-healing properties, thus ensuring long term stability of the structure.

Keywords: Topological Interlocking, Hybrid Elements, Self-healing.

1 Introduction

Exploration and colonisation of Mars and small planets (the Moon and asteroids) will at some point require establishing permanent habitable bases or colonies. The challenge of extraterrestrial construction lies in the detrimental conditions such habitats will be exposed to. These include (1) radiation [1]; (2) extreme temperatures and their variations; (3) very low atmospheric pressure combined with strong dust storms observed in Martian atmosphere and possibly levitating dust [2, 3]; (4) possibility of meteoritic and errant vehicle impact, especially in the adverse environment unusual for human experience.

These conditions place special restrictions on the choice of types of structures and construction methods, the most stringent being the radiation protection. While a short-term base can have radiation protection similar to that of the International Space Station, a long-term base will have to face more stringent requirements. In particular, the walls have to much thicker than in the space ship and hence will have to be built in-situ. Two main methods of radiation protection currently proposed are (e.g., [1, 7]): (1) building the station underground to use the natural rock for protection; (2) erecting regolith protective shield around the station placed fully or partly above the ground.

The first option is attractive in the lunar environment where the utilisation of lunar lava tubes is envisaged. However, in the absence of natural underground shelters, this option involves considerable mining operations with the use of heavy equipment, whose delivery might be prohibitively expensive. The second option requires 'earth' moving operations to place regolith around the base.

In this paper we propose an alternative solution: to assemble a long-term base out of hybrid interlocking blocks consisting of deployable pre-fabricated shells filled *in-situ* with regolith and special pre-fabricated elements that provide lateral constraint to the walls, floor and roof. When joined together, the interlocking property of the blocks will ensure the integrity of the entire structure.

2 Hybrid interlocking structural elements

2.1 Hybrid structural element: Pre-fabricated shell filled with regolith

The traditional construction methods are based on (1) pre-fabricated or *in-situ* cast concrete elements; (2) metal/glass/plastic pre-fabricated elements; (3) bricks or; (4) stone blocks. Obviously, the use of pre-fabricated concrete elements can be ruled out, as the transportation of these heavy structures is not a realistic option. *In-situ* manufacturing is possible in principle (e.g. [5]), however it would require the construction of cement producing plants and a supply of water. The same requirements apply for the construction based on bricks or blocks, additional efforts and cost being necessary for brick production or *in-situ* extraction and polishing of natural stone (provided the stone of required quality is available near the construction site in the first place). However, the major impediment for the cement/mortar based construction is the very low atmospheric pressure. Curing under low pressure considerably reduces strength of cement due to water evaporation and subsequent foaming of the cement [8]. This circumstance essentially rules out the use of mortar as a binder and makes manufacturing of pre-cast concrete structural elements very expensive as it would require curing in a pressurised chamber.

The use of pre-fabricated metal/glass/plastic elements, especially from the light-weight materials or inflatable structures (e.g., [6]) is another option. However, the need for protection against radiation and extreme temperature variations necessitate the structures to be of considerable thickness and mass. The latter is also required to enhance stability of the structure in view of the low gravity. This makes it necessary to combine the transported pre-fabricated structures with the *in-situ* materials that can ensure the required thickness and mass.

Combining pre-fabricated structures refined to ensure good service properties and low weight with rough *in-situ* material can be a challenge. We propose to use pre-fabricated shells filled by regolith material and stones extracted in-situ. From the materials engineering point of view, the proposed construction from hybrid elements falls into the realm of hybrid materials which are 'combinations of two or more materials in a predetermined geometry and scale, optimally serving a specific engineering purpose' [14]. In this case the walls of the base form a mechanical combination of the interlockable blocks made of a shell material (e.g., aluminium), whose purpose is to provide the right shape to the elements, with regolith which provides compressive strength as well as the radiation and thermal protection.

The use of regolith in the form of *in-situ* fabricated bricks of traditional shape has already been proposed [15, 16]. However the construction requires a binder or another method of connecting blocks within the structure. Because of low gravity, the self-weight of the bricks cannot be considered as a structure stabiliser. Mortar cannot be used since curing under low atmospheric pressure leads to considerable strength reduction. Thus, one is bound to use welding or another form of joining, which in the case of hybrid blocks requires considerable thickness of the shells to ensure the necessary strength of the connections. This will increase the weight of the pre-fabricated shells and the transportation cost.

In this situation, the use of interlocking blocks is the method of choice [9]. Traditional interlocking involves the LEGO-type blocks with special keys or connectors. This would require relatively high precision of manufacturing, which is sensitive to dust deposition on or the dust abrasion of the contact surfaces. It is attractive to use another type of interlocking – the so-called topological interlocking [10-12]. In [13] we proposed the use of topological interlocking in extraterrestrial construction based on interlocking blocks with curved surfaces (osteomorphic blocks, Fig. 1). Despite many advantages, such as relative ease of construction and high stability, the major impediment is the difficulty of their *in-situ* manufacture. Due to the special shape, casting in a mould is required, which is difficult under the low atmospheric pressure unless special methods, such as selective laser sintering, are used. This technology is still in its infancy, and no sintering method has been successfully applied to regolith as yet. Pre-fabricated shells of osteomorphic shape, though possible, would require fine graded regolith to be used as filler, and the use of special compaction methods for the sharp corners of the shell. Also because of the curved surfaces they are not very convenient for transportation.

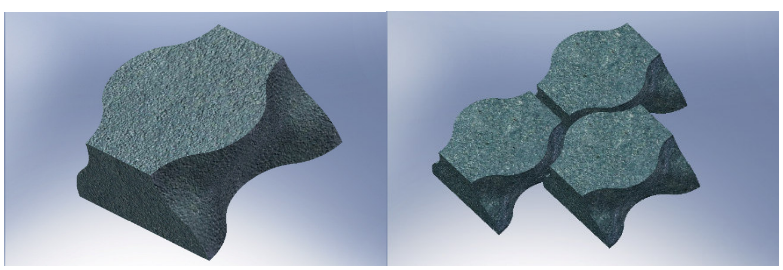

Fig. 1. Topological interlocking with osteomorphic blocks [12].

As the use of the osteomorphic blocks may be difficult, we propose to use blocks in the shape of regular polyhedra. Shells of these shapes can be delivered as nets with the subsequent *in-situ* deployment. All Platonic solids (tetrahedron, cube, octahedron, dodecahedron and icosahedron) are interlockable [11], so the choice is dictated by the ease of filling and compacting regolith and the convenience of assembling the structures. Dodecahedron and icosahedron have very low degree of interlocking, which leaves us with tetrahedron, cube and octahedron. Of these, only octahedra are easy to assemble as they have one of the faces parallel to the assembled layer.

2.2. Interlocking of octahedra and octahedral shells

As discussed above, the shape of choice for this construction method is octahedron, Fig. 2a. The sketch demonstrates that an attempt to remove any internal block from the assembly in both directions normal to the plane of the assembly will cause lateral movement of some of the neighbours. Thus if the peripheral blocks are fixed, for instance by a frame that provides the lateral constraint, the whole assembly will maintain its integrity despite the blocks not being bound or joined in any way.

A characteristic feature of the assemblies of topologically interlocked elements is that only part of each face of the neighbouring elements is in contact. In particular, the triangular faces of octahedra contact each other only through a rhombus-shaped part of an octahedron face, Fig. 2b. The contact area makes up only 1/2 of the face area.

Fig. 3a shows the net for an octahedron which can be used as a prototype for a pre-fabricated transportable sheet consisting of 8 regular triangles connected by hinges. The hinges allow *in-situ* folding of the sheet into tetrahedron with open upper face which is used as a lid after the shell is filled with regolith, Fig. 3b.

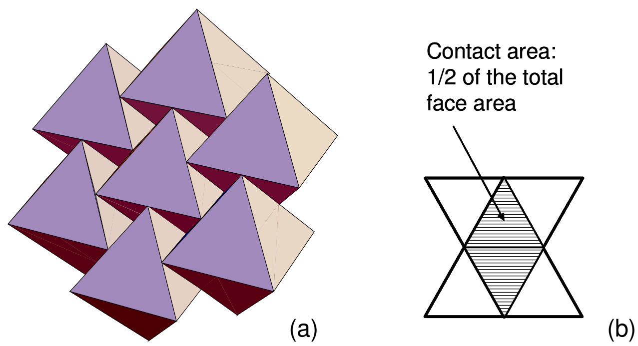

Fig. 2. Topological interlocking of octahedra: (a) assembly; (b) the contact area.

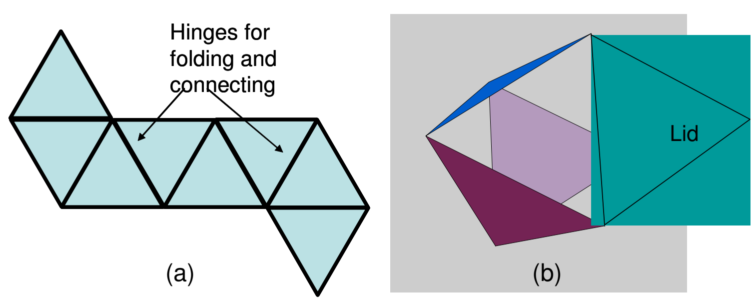

Fig. 3. Octahedron-shape shell: (a) in a flat form for transportation purposes; (b) after deployment. The upper face serves as a lid.

3 Structure of the base

The main structure forming the base consists of six interlocking assemblies forming the floor, the walls and the roof. These are connected together via elements of a frame, Fig. 4. The profile of the frame is to match the non-planar edges of the assemblies and to provide the lateral constraint. The thickness of the assemblies (the size of the octahedral hybrid elements) should be at least 1 m such that the thinnest part of it (the one opposite a depression) is 0.5 m thick - the thickness sufficient for a long-term radiation protection [1].

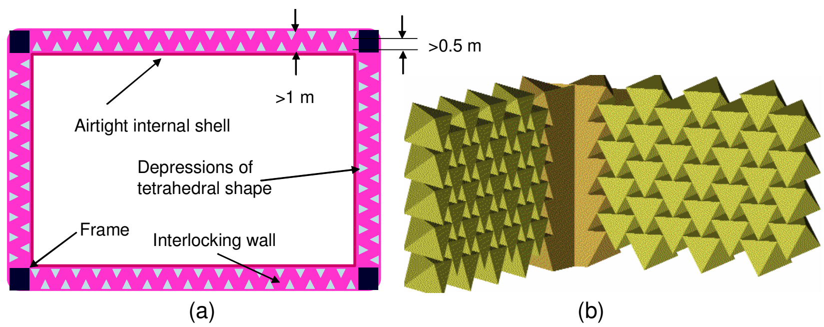

Fig. 4. Layout of the base structure: (a) the frame which ensures lateral constraint. The depressions are manifestations of partial contact between the octahedra; (b) a corner.

4 Fracture resistance and self-healing

The assemblies of topologically interlocking elements possess high fracture resistance, essentially containing the fracture within a block, and are capable of withstanding multiple fractures before the whole structure ultimately fails [17-18]. The localisation of fracture is essential for express damage repair after the structure is hit by a meteorite or errant vehicle.

A recent discovery [19] shows that the interlocking structures exhibit a vibration-induced self-healing behaviour. It was proven using physical models of both osteomorphic bock structures and properly assembled dry stone structures that after being dented (blocks shifted out of the structure by indentation) can regain its original shape if vibrations with a certain frequency are applied.

The mechanism of this self-healing lies in the nature of topological interlocking. The same force which, in the presence of a lateral constraint, prevents a block from its leaving the assembly pushes the block back once it is displaced. Friction between the contacting surfaces obstructs that movement. If the system is subjected to vibrations at the resonance frequency, the blocks get temporarily separated and lose contact friction which allows the displaced block to be returned back into position.

The self-healing capability is important for the longevity of the structure as it utilises natural vibrations (e.g. caused by the ground vehicles or space ship launch) to recover the original shape of the structure and thus prolong its service life.

5 Conclusions

Building long-term Martian bases requires structures with a sufficient level of protection against radiation, extreme temperatures and impacts. This implies that the outer walls and the roof of the base should be of considerable thickness, which rules out the option of building them from pre-fabricated delivered elements. Building a station from the elements manufactured entirely *in-situ* is also difficult due to problems with manufacturing cementitious materials and their curing under low atmospheric pressures. We propose a new construction principle based on the hybrid blocks made of pre-fabricated and delivered shells filled *in-situ* by regolith. In order to avoid the difficulties with joining the blocks, we propose to use octahedron-shaped building blocks which can be interlocked topologically. Structures based on topological interlocking do not require binder to keep their integrity. There are a number of issues for further research such as the shell material, the required grade and quality of regolith, dimensions of the structures that are possible to achieve, tension in the frame necessary to achieve the structural stability against internal pressurisation, add-ons such as airlocks, etc. Nevertheless, the simplicity of construction and the long term stability underpinned by high fracture resistance and self-healing create a potential for the proposed concept to be used in extraterrestrial *in situ* construction.

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