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Research on Ventilation and Heat Insulation Layer Design of Split-Type Roof Greening Based on Topological Interlocking Principle

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Abstract: In this paper, the roof ventilation and heat insulation layer modules are combined with the roof greening, and each module is assembled through the principle of topological interlocking. The assembly of these modules does not require any rivets or cement mortar, and the structural stability of the overall assembled roof is achieved only through the interlocking and limiting the movements of the interlocked units. The green roof designed in this paper has strong applicability and can be applied to roofs of different shapes. Such a roof can not only meet the aesthetic needs, but also beautify the urban environment and reduce carbon emissions.

Keywords: Roof greening; Overhead insulated roof; Topological interlocking; Module

1. Introduction

Roof greening is more and more widely used as the awareness towards environmental protection increases. Besides, green roofs also play a role in the heat insulation of the building. Roof ventilation can reduce the indoor temperature of the building, increase comfort, and reduce the energy consumption of air-conditioning systems. Considering the advantages of both roof greening and ventilation, a modular roof with the functions of planting, greening and ventilation was designed, which will be described in this paper. These modules feature interlocking shapes that are misaligned and woven together, eliminating the need for mortar masonry and metal connectors. This design prevents aging and corrosion, enabling them to function as a permanent part of the building structure. Furthermore, these modules are easy to construct, have low maintenance costs, and can be disassembled and reassembled as needed.

2. Roof greening and construction of the insulation layer

2.1. Roof greening

Green plants have functions such as regulating air temperature and humidity, absorbing solar radiation, and absorbing external noise. The roof is called the “fifth façade" of the building. Green roofs primarily serve to enhance the aesthetics of building rooftops, protect the urban environment, and enhance living conditions. Furthermore, they contribute to thermal insulation, elevated air humidity, and noise absorption by incorporating green vegetation on the roof.

Traditional methods of roof greening include roof lawns, roof gardens, and container gardening. Container gardening involves utilizing prefabricated flowerpots that can be flexibly combined, causing minimal disruption to the existing roof while allowing for versatile layouts. However, there are some problems in using flowerpots. Flowerpots for container gardening are usually made of plastic, which is less durable. The flowerpots need to be placed under the sun, which makes them age faster. Besides, harmful gases are released when plastic ages, causing environmental pollution. These containers generally require other connectors, such as plastic or metal components, which are also prone to aging and rust, causing environmental pollution. These plastic products are often not strong enough to bear a heavy covering soil layer. Container gardening is suitable for simple plants or shallow-rooted shrubs but lack proper ventilation. There are also flowerpots made of materials like concrete, but they are less flexible and require cement mortar for anchoring.

2. 2. Overhead heat insulation roof

The main function of an overhead heat insulation roof is to prevent solar radiation from directly irradiating the roof. Solar radiation can keep the air circulation between the overhead layer and the roof layer, and take away the hot air through thermal convection, resulting in thermal insulation. However, overhead heat insulation roof is often used on the roofs of older houses, which lack sufficient insulation conditions. And it is not combined with the green roof, so the insulation effect is relatively less than ideal. There are a few types of traditional overhead heat insulation roof. They are usually made of cement mortar, and they are relatively thin. Even with mortar, they are still not strong enough to resist extreme weather such as strong wind and heavy rain. In addition, because the traditional overhead heat insulation roof is made of masonry, it is not easily replaceable once it is damaged.

2. 3. Flat roof

A roof consists of a steam layer, thermal insulation layer, waterproof layer, and protective layer. There are no gaps in the structural layers of the roof, so the heat insulation of the roof depends only on the thermal insulation performance of the material itself. In areas with strong solar radiation, the heat from the sun is directly transferred to the structural layer on the roof, and the heat gets trapped in the layers of the roof. Besides, flat roofs are monotonous and unattractive without any greening. Ordinary flat roofs have simple structures and functions, yet they demand significant energy consumption for indoor comfort, which contradicts modern energy efficiency goals and China ′s dual carbon policy focused on emission reduction[1].

3. Principle of topological interlocking

3. 1. The concept of topological interlocking

The term “topological interlocking” has two meanings, namely “topology” and “interlocking.” Mathematically, “topology” means that a geometric object still maintains some original characteristics after continuous deformation. For instance, a stick and a sphere share the same topology, so do a ring and a pipe. “Interlocking” indicates that objects are joined in a way that prevents relative movement, creating overall stability. The combination of these two terms implies that a collection of units sharing the same topology are arranged in a way that limits their relative movement, resulting in a stable cluster where individual blocks cannot be detached. This is achieved through specific geometric shapes and arrangement (except for blocks at borders, which will be discussed separately)[2].

As early as the 18th century, in the book *La theorie et la pratique de la coupe des pierres et des bois,* *pour la construction des voutes et autres parties des bâtimens civils & militaires, ou traité de stereotomie a l' usage de l' architecture*, Volume 2, Joseph Abeille an engineer and architect designed a flat vault and some block units that conform to the concept of topological interlocking (Figure 1)[3]. These block units can cover a certain area without the use of mortar, cementing materials, or trapezoidal stones. This structure is easy to disassemble and can be reused. The concept of topological interlocking was proposed academically by Dyskin *et al.* in 2001. The simplest topologically interlocked structure is a single-layer tetrahedron, and various topologically interlocked basic units can be derived through deformation in the topological sense[4]. Topological interlocking units and their arrangement have since become an important part of the field of material design. For example, researchers have used the unique properties of these interlocking units to create protective gear like body armor.

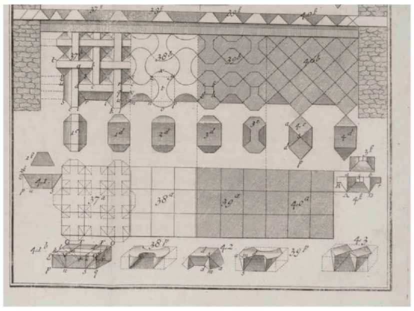


Figure 1　Drawings of some interlocking blocks designed by Joseph Abeille

Topological interlocking units can be divided into platonic solid and osteomorphic blocks. Platonic solid is a convex polyhedron with topological interlocking features. Dyskin initially confirmed that tetrahedrons can be interlocked through a specific arrangement (Figure 2). Subsequent research further confirmed that shapes like cubes, octahedrons, and other polyhedrons with twelve sides can achieve topological interlocking. These convex polyhedrons belong to the category of platonic solids. Osteomorphic blocks typically have curved edges, differing from traditional polyhedrons. Their shapes resemble bones, and the interlocking of their concave and convex contact surfaces also exhibits characteristics of topological interlocking.

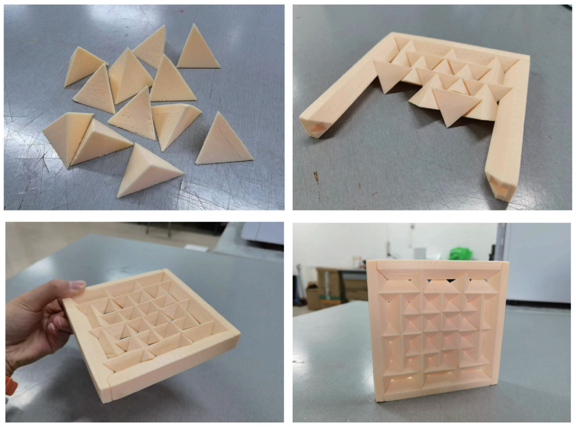
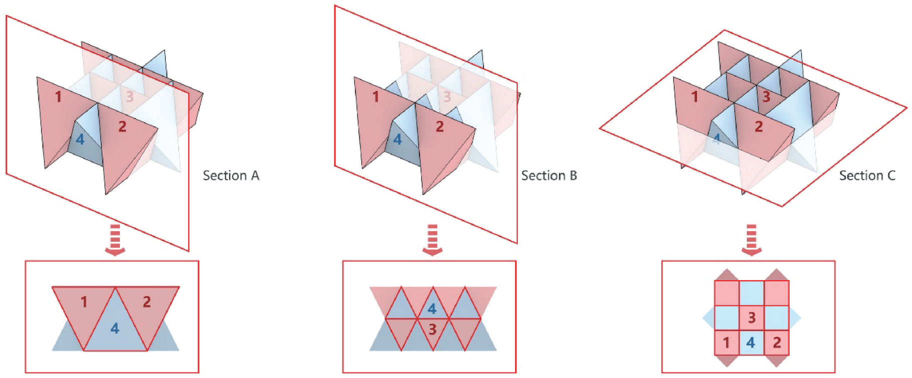


Figure 2　Tetrahedral topological interlocking walls

3. 2. The locking principle of topological interlocking

To determine if a system achieves interlocking, two criteria are used: translational interlock and rotational interlock. In a group of units, if the units around a specific unit prevent that unit from moving away through translation, it can be said that the unit achieves translational interlock. Rotation interlock is also determined the same way. Furthermore, if all units in the system cannot be moved through translation (or rotation), then these units are considered translationally interlocked (or rotationally interlocked). A unit type is fully interlocked if the unit is both translationally and rotationally interlocked[5].

The mechanisms of forming interlocking units have been described in several works. According to Dyskin, if an element within an interlocking system is constrained by the kinematics of its neighboring units in one direction perpendicular to the assembly plane, while also being constrained in the opposite direction by the kinematics of other neighboring units, then interlocking is achieved[6]. Taking the most basic topological interlocking unit — tetrahedron as an example, in section A, the upward movement of module 4 is limited by modules 1 and 2 (Figure 3a); while in section B, the downward movement of module 4 is defined by module 3 (Figure 3b), thus the movement of module 4 in the up and down direction is fully defined; in section C (horizontal section in the middle position), the movement of module 3 is limited by the 4 blue modules at the periphery (Figure 3c). In short, the module' s translational movement in three-dimensional space is fully restricted, achieving translational interlocking. This design principle was subsequently applied in the development of structures called osteoids.



a. Upward movement is limited

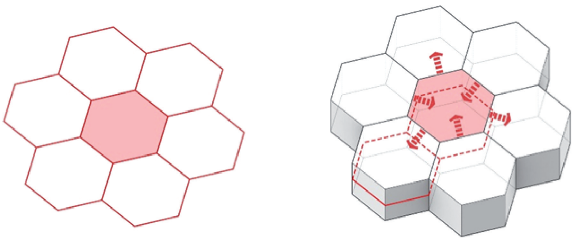
b. Downward movement is limited

c. Horizontal movement is limited

Figure 3 Interlocking principles of topological interlocking explained based on cross-sections at different locations

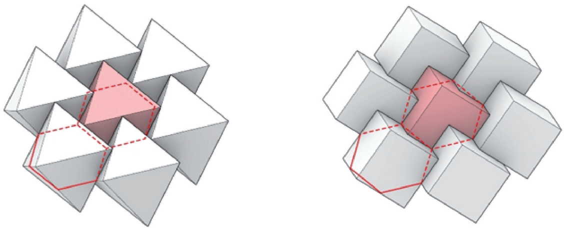
3.3. The logic behind forming a topological interlocking unit

By applying the interlocking principles discussed earlier, we can deduce the underlying logic behind the creation of topologically interlocked structures. Taking cubes and octahedron as examples, a regular hexagonal mosaic grid is established first, and the plane is used as the middle section plane of the interlocking unit (Figure 4a). By extruding each regular hexagonal unit upwards and downwards, regular hexagonal prisms are obtained (Figure 4b). The hexagonal top edges located above the middle section plane are alternately offset in the direction of the arrow, while the hexagonal bottom edges located below the middle section plane are alternately offset in the opposite direction. As the offset progresses, the three sides that were offset outward eventually converge into points. Consequently, the top and bottom surfaces turn into regular triangles, transforming the entire regular hexagonal prism unit into an octahedron (Figure 4c). If the three sides connected to the top surface and the bottom surface extend upwards, causing the top and bottom surfaces to translate and extend upwards and downwards respectively, the areas of these surfaces continue to shrink until they ultimately become a point. This results in a cube interlocking unit (Figure 4 d).



a. Create a regular hexagonal tessellation as the mid-section plane

b. Extrude the section plane upwards and downwards respectively



c. The interlocking unit of the octahedron can be obtained by offsetting the edge in the direction of the arrow in Figure b

b. The three sides of the top triangle extending upwards can intersect at a point, which results in cubic interlocking units

Figure 4　Generation process of octahedron and cube interlocking unit

The aforementioned logic can be applied to the generation of various other topologically interlocked units, including Platonic solids such as dodecahedrons, icosahedrons, and even Buckyballs[5]. In short, the concept of topological interlocking units can be simplified into a basic model (Figure 5). This simplified model allows a more intuitive understanding of Dyskin's criterion for interlocking convex polyhedrons. By manipulating the normals of a row of units within the section, the edges situated above and below the middle section plane are translated in opposite directions. This setup ensures that the upper and lower sides of the middle section plane impose movement constraints in corresponding directions, thus effectively achieving unit interlocking.

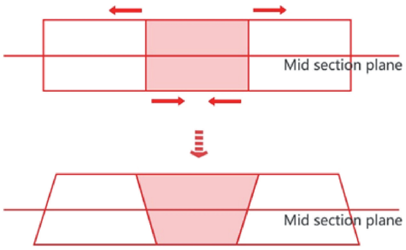


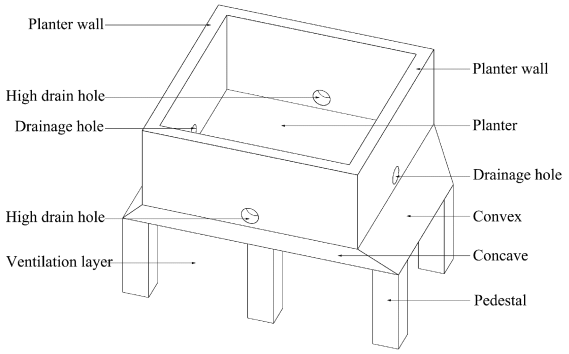
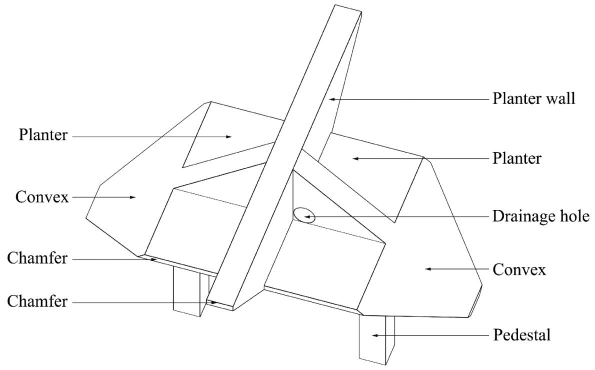
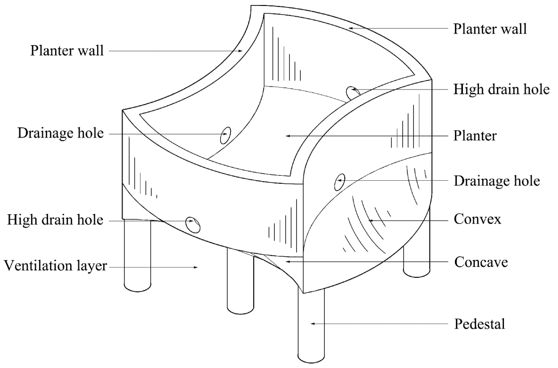
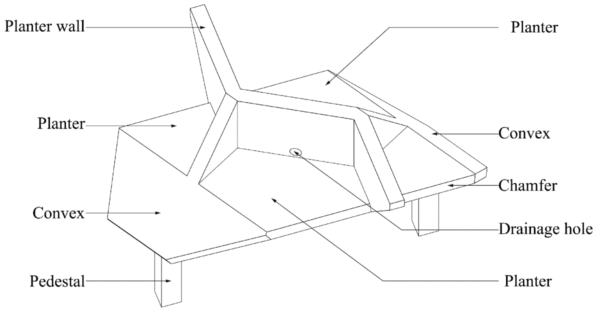
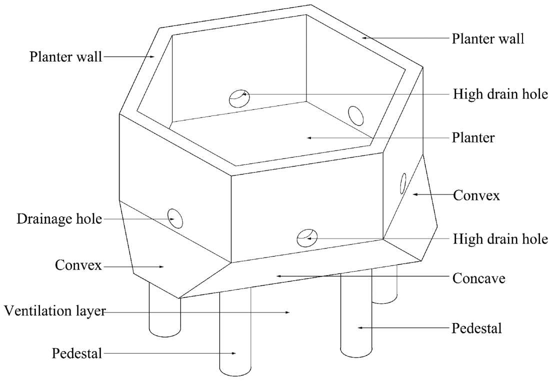
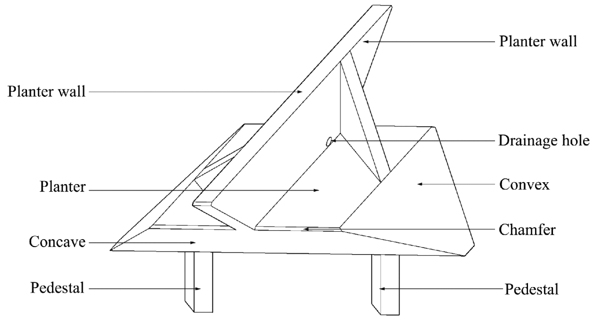
Figure 5　A simple generation model of topological interlocking units

4. Roof greening thermal insulation layer based on the principle of topological interlocking

The complete thermal insulation layer for roof greening is constructed using fundamental units, complemented by side units. The primary role of the central basic unit lies in planting and ventilating, while the side unit modules on the north and south sides mainly serve the purpose of ventilating. According to the formation mode of the planting trough, the modules designed in this paper can be divided into two categories, one is that each module comes with a complete planter, numbered as type A, and the other is that multiple modules are combined to form a complete planter, numbered as type B. The trough planters are labeled as Class B. Within Class A modules, based on the configuration of the central interlocking unit, further categorization can be made into Class A1, A2, and A3. These correspond to quadrilateral interlocking units, osteoid interlocking units, and hexagonal interlocking units, respectively.

The Class B module can also be subdivided into three types: B1, B2, and B3, which corresponds to quadrilateral interlocking units and two different forms of prismatic interlocking units respectively (Table 1).

Table 1 Type A and Type B basic unit modules

Basic unit module	Type A	Type B
1		
2		
3		

4.1. Design of basic unit modules

The basic unit module is composed of 3 parts, the upper part consists of a planting groove, the middle part consists of the interlocking unit and the lower part is the pedestal. The structure of the upper planter trough is similar to that of a green roof, and is equipped with drainage holes to remove excess water. The width of the planter trough is 25–80 mm, preferably 40 mm, with a height of 300–1 200 mm. The width of planter trough varies with different module types, generally in the range of 400–2400 mm. In type A modules, each planter wall has a drainage hole: A1 and A2 modules have 4 drainage holes, A3 module has 6 drainage holes, and all three types of modules include 2 high-level drainage holes. In the type B module, drainage holes are also found on the planter wall. In addition, there is also a drainage hole in the middle of the planter. The drainage holes on the walls of the planter troughs of different modules are set in the same position. When splicing, the drainage holes are opposite to each other, which can ensure that the water levels between different modules are connected. In this way, the excess water in the planting trough can eventually flow to the unit modules on the east and west sides. Drainage grooves are created at the drainage holes of the modules on both sides. The excess water can be directly discharged to the gutters on the roof, and then discharged from the roof through the drainage pipes.

The interlocking unit in the middle is the key to realizing topological interlocking. In order to prevent this part from being too heavy, there are certain grooves in the lower part to reduce weight and save materials. The inclination angle of the sides of the interlocking unit is 35–50°, preferably 45°. A suitable inclination angle of the sides allows for more stable interlocking. In a type A module, taking the A1 module as an example, the concave surface of a basic unit module is connected to the convex surface of an adjacent module, and the convex surface of the module is connected to the concave surface of another adjacent module, so that interlocking is achieved, forming a stable structure. The same applies to A2 and A3 modules. In the type B module, the interlocking method is similar to that of the type A module, and interlocking is achieved by joining the concave surface to the convex surface. The difference is that their planter walls are also concave or convex extensions that also participate in the interlocking.

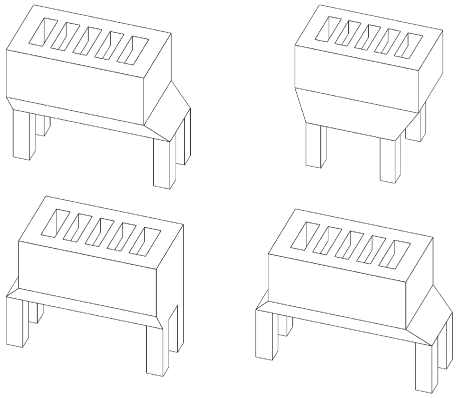
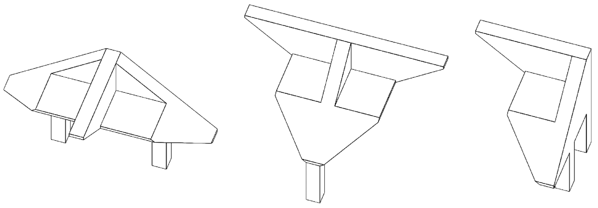
The lower pillars serve mainly to support the overall structure and facilitate ventilation. The number of pillars in the type A module corresponds to the sides of the planter walls, while for type B modules, there are generally two pillars. The recommended height for these lower pillars ranges from 150 to 500 mm, with 200 mm being the preferred choice. The primary function of this section is to elevate the modules, creating a raised layer between the green area and the roof. This structure functions similarly to an overhead roof. The upper planted roof absorbs solar radiation, resulting in heating and the consequent thermal convection of air within the overhead layer. This convection expels heated air, effectively achieving thermal insulation.

4.2. Design of the edge unit modules

In addition to a large number of basic unit modules, the entire green roof insulation layer also includes side unit modules located at the parapet. The side unit modules have a fundamental role in connecting with the parapet wall and filling any excessive gaps resulting from the shape differences between the basic unit module and the parapet wall. Depending on their placement, the side unit modules can be categorized into those positioned on the north and south sides and those located on the east and west sides. The structure of the side unit module is similar to that of the basic unit module, including the interlocking unit part in the middle and the pedestals in the lower part. The difference is that the upper part of the side unit modules located on the north and south sides is a vent. The primary purpose of the vent is to facilitate the airflow between the overhead layer and the external environment, allowing the warm air created by the thermal convection of the overhead layer to be expelled, thereby achieving thermal insulation. Typically, the side unit module has dimensions roughly half that of the basic unit module in one direction, while the remaining dimensions align with those of the basic unit module (Table 2).

Among the A-type modules, the A1 module only requires the installation of side unit modules with vents on the north and south sides because of its regular shape, and side unit modules are not needed on the east and west sides. The side units of the A2 module are similar to those of the A1. Although there are certain gaps on the east and west sides, the gap width is small and can be ignored. The A3 module not only requires side unit modules on the north and south sides, but also the east and west sides due to its larger gap. Type-B modules require a variety of side unit modules due to their more complex shape compared to type A. Corner unit modules are also needed to fill the gaps at the roof corners.

Table 2 Type A1 and Type B1 side unit modules

Basic unit module	Type A1	Type B1
1		

4. 3. Properties of split-type green roof insulation layer from the perspective of the topological interlocking principle

The insulation layer is mainly composed of side unit modules for ventilation on the north and south borders and basic unit modules for planting in the middle. The basic unit module in the middle acts as a thermal insulator, blocking the direct effect of solar radiation, and the ventilation layer below acts as a vent. The north and south side unit modules facilitate the exchange and circulation of air between the overhead section and the external environment through vents, removing excess heat and protecting the building from intense solar radiation.

The thermal insulation layer designed in this paper is composed of several unit modules. Each module can be prefabricated in the factory or fabricated on site. This design is container-gardening-based, which is in line with the current trend of BIM and prefabricated buildings in China[7]. The finished modules can be assembled on-site. The process of assembling is simple. Besides, the modules are easy to transport. By growing the plants before installation, they can be directly placed onto the roof along with waterproof and irrigation systems once they mature. This approach ensures higher plant survival rates and enhances the overall landscaping effect.

The module adopts the principle of topological interlocking. The advantage of topological interlocking is that the green roof can be modularized. This allows for easy disassembly and recombination. Once combined, it achieves a high level of overall stability. The topological interlocking unit module has the characteristic of small-amplitude motion within the kinematic constraints of realizing interlocking, which can avoid the failure of the whole system under the influence of high-amplitude vibration and dissipative vibration. This is mainly because the mobility of the topological interlocking structure absorbs part of the vibration energy, so this module has very superior seismic performance[8]. In addition, when a crack occurs in a module in the system, the modular design can prevent the crack from spreading to other adjacent modules, which might result in the destruction of the whole system[4].

The method of topology interlocking assembly reduces the need for numerous metal connectors and plastic parts, while also avoiding issues such as metal corrosion and plastic aging. The plants can be watered by simple spraying. The modules exhibit robust anti-aging properties, and when integrated with the building structure, they become a permanent part of the building. Its maintenance is straightforward with minimal costs. In case of damage to specific modules due to unique circumstances, the components can be disassembled and replaced easily, as there are no rigid connections between individual modules.

5. Practical application

5. 1. Production process

The module designed in this paper can be made of several materials, such as concrete, shale, coal gangue, fly ash, lime sand, etc. It can also be made with local specialty materials or abandoned construction waste that are crushed and processed according to local conditions, which can effectively reduce costs. Once the raw materials are processed and shaped, they can undergo pouring, sintering, cold pressing, or autoclaving. The manufacturing process for modules has minimal requirements. Moreover, secondary processing of industrial and construction waste is both energy-efficient and environmentally friendly (Figure 6).

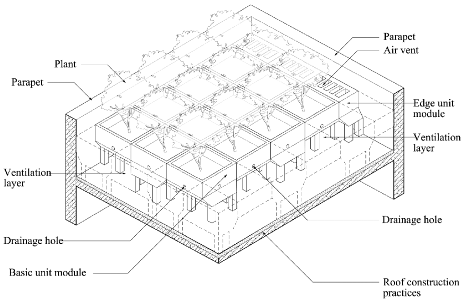
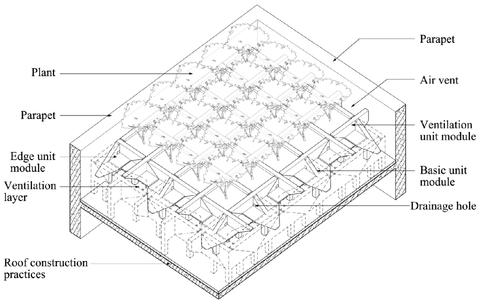
Figure 6　Type A1 and type B1 basic unit module concrete model

5. 2. Process of assembling the modules

For the assembly of the green roof module, the side unit modules are first installed on the north side of the roof, and then the corresponding basic unit modules are assembled sequentially from north to south according to the principle of topological interlocking (the installation of the side unit modules on the east and west sides is needed for some modules). It is important to ensure that the concave surface and the convex surface of the module are joint tightly. After completing the erection of the basic unit modules, the corresponding side unit modules are used to fill the vacancy on the south side, thus completing the assembly of the entire roof (Table 3 and Figure 7).

The structure of the basic unit module is similar to that of the green roof. After the roof is assembled, the corresponding layers are laid in the planter trough sequentially. The aquifer has the function of draining excess water and storing water, and the height of the drainage aquifer is the same as the height of the drainage holes on the wall of the planter. During a heavy rain, excess water can flow through the aquifer to the drainage hole, and finally to an open ditch or gutter. The thickness of the soil layer needs to be adjusted according to the type of plants, but the total height should be lower than the height of the planter trough.

Table 3 Type A1 and type B1 modular roof assembly method

Basic unit module	Type A1	Type B1
1		

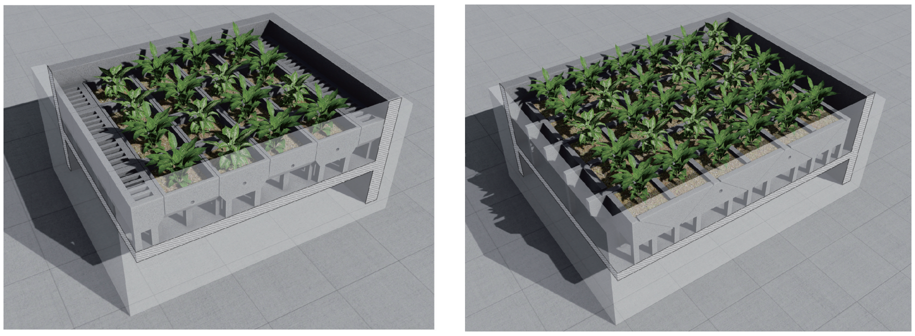


Figure 7 Rendering of A1 and B1 module roof assembly

6. Conclusion

This paper introduces a split-type green roof insulation design by blending the benefits of existing roof greening and overhead insulation methods while incorporating the principle of topological interlocking. While the theoretical aspects of topological interlocking have been studied for a while, practical applications have been limited. This study extensively explores the interlocking and generation principle of topological interlocking, utilizing its unique characteristics to create a series of interconnected modules that enhance both roof stability and aesthetics through planting and greening. This module series integrates the advantages of green roofs and overhead insulation layers, resulting in efficient heat insulation. Without the need for metal or plastic connectors, the modules exhibit robust weather resistance and can coexist as permanent structures with the building. Its maintenance is straightforward and cost-effective. The proposed module series addresses the limitations of current roof insulation systems, enhancing roof greening, insulation, and efforts to reduce carbon emissions. This advancement holds significant implications.

Disclosure statement

The author declares no conflict of interest.

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