Frontiers of Architectural Research 10 (2021) 758–770

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RESEARCH ARTICLE

Lego architecture: Research on a temporary building design method for post-disaster emergency

Daoyuan Chen*, **Guoen Wang**, **Guojun Chen**

School of Urban Design, Wuhan University, Wuhan, 430072, China

Received 12 April 2021; received in revised form 19 July 2021; accepted 8 August 2021

KEYWORDS
Discrete architecture;
Lego architecture;
Temporary buildings;
Portable buildings;
Recyclable

Abstract Disasters are becoming the norm in this world, which also poses challenges to architects. Many needs to build temporary buildings may occur at the same time randomly around all over the world. Constructing an efficient and economical solution is the motivation of this research. Through a comprehensive review of all past related researches and architectural practices, "convenience" and "recyclability" have been identified as two important features of temporary buildings in the post-pandemic era. In this article, we carry on a novel research of discrete architecture. Based on the design paradigm of discrete architecture, this research uses the three main components of S/U/P to develop a Lego Architecture design method by combining with the Grasshopper plug-in under the Rhino platform to write a program that automatically generates the target plan. Then, a typical design scheme for physical construction verification and structural optimization is selected to ensure landing and safety. Originating from the thinking of productization, this research attempts to package the design methods and related knowledge into a systematic solution, relying on an open construction system framework to achieve a rapid, simple and safe construction of temporary buildings after disasters.
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* Corresponding author.
E-mail address: daoyuan.chen@whu.edu.cn (D. Chen).
Peer review under responsibility of Southeast University.

https://doi.org/10.1016/j.foar.2021.08.001
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1. Introduction

As stated in the Intergovernmental Panel on Climate Change (IPCC), cities are becoming more and more vulnerable to the impact of natural disasters, and their frequency, duration and intensity will become increasingly extreme (Bai et al., 2018). The COVID-19 epidemic that began in 2020 has confirmed this prediction. Modern cities and human society are facing unprecedented challenges. In order to withstand the damage caused by the disaster, we have witnessed the Fangcang shelter hospitals established in China within a few days (Chen et al., 2020), and we have also witnessed the recyclable temporary shelter units built by Turkey at very low cost after the earthquake (Arslan, 2007). However, existing researches often focus only on meeting the specific building performance needs of the target post-disaster group, and seldom think about the potential composition and final form of temporary buildings from the perspective of structure and construction activities themselves. There are also few construction products that combine the characteristics of rapid construction, low cost, and mass production.

This article aims to identify the key features of temporary buildings in the post-epidemic era, and then select some appropriate design methods and combine parametric calculation tools to construct a set of programs that automatically generate design schemes according to task requirements. Our research team simplifies the types of design components as much as possible and packaged them into building products under a unified system for users in more regions. Specifically, this research attempts to answer the following three questions:

(1) In the new era, especially in the post-pandemic era, is there any change in human demand for temporary buildings? If the change occurs, what characteristics will these buildings show in the future?
(2) What is a Lego-like architecture? How to use the idea of Lego bricks in architectural design? If Lego logic is used, how to achieve the similar Interlocking connections between various parts of the building? What does the specific node design look like?
(3) How is the SUP system created step by step? Can a building structure without nails, glue, and metal welding be stably constructed? Is the construction cost of the system low enough to replace the current containerized assembly building system?

The following is specifically elaborated in four parts: literature review, research perspective, SUP system introduction, discussion and summary, to demonstrate the huge potential of self-interlocking structure in the design of temporary buildings.

2. Literature review

2.1. The origin of temporary buildings

Temporary building can be traced back to the movable tents of nomads. With the development of construction industry technology, temporary buildings have begun to become a type of architecture. This type of building is often accompanied by the need for rapid construction. For example, in 1851, it only took less than 9 months to complete the construction of the Crystal Palace at the London World Expo, which can also be disassembled and transported to another place for reassembly. After World War II, the demand for reconstruction of housing and other buildings rose rapidly in various countries. In the 1960s, a large number of simple buildings composed of precast concrete boxes appeared in the United Kingdom and Europe. But at the same time, the spectacular collapse of the Ronan Point tower block was caused by its structural defects (Gibb, 1999). Later, represented by the "plug-in city" based on movable "cabin houses" proposed by Peter Cook in 1964, the Archigram group criticized and responded to what they considered dull and conservative modern architecture at the time (Sadler, 2005). Under the principle of flexibility and variability, several buildings and urban forms with great adaptability characteristics were conceived.

At the same time, Japan emerged as "metabolism" architects who promoted prefabricated buildings and proposed that urban buildings should be renewed like biological cell metabolism, an organic evolutionary process of constant extinction and creation (Schalk, 2014). For example, Nakagin Capsule Tower, the world's first capsule building, is a masterpiece of this type of prefabricated assembly technology practice. In general, the improvement of social productivity has brought about an unprecedented consumption era. The construction industry also showed some similar characteristics after the 1960s. A large number of buildings were demolished decades or even years after they were built. Their update speed has been much faster than any previous period.

2.2. From fast to portable, from disposable to recyclable

In the past researches and practices, designers and users tended to focus more on the "fastness" of construction activities; at the same time, due to the constraints of objective conditions, more non-recyclable economic materials such as concrete were used as the main body of many constructions. After this wave of temporary buildings, many scholars and designers called for the improved design methods in response to many problems such as rigid structures and a waste of materials. In terms of portable architecture, Robert Kronenburg has conducted in-depth research for decades, where many advantages and conveniences of portable buildings has discussed. He believes that its not the only aim for architectures in a dynamically changing environment to pursuing the permanence, where architectures should also be recyclable and modifiable (Kronenburg, 2013). The same view was also confirmed in "*Mobile: the Art of Portable Architecture*". Jennifer Siegal discussed the importance of mobile buildings for the construction and development of modern cities, and introduced several common mobile building styles and cases (Siegal, 2002).

In terms of material recyclability, Ryan E. Smith reviewed the historical development of building industrialization, combined with the emergence of computer-assisted construction technology in recent years, believed that offsite construction presents the opportunity for the high level of "total sustainability" through integration, document and supply controls, and material management (Smith, 2010). Jure Kotnik also used a large number of cases in the book "*Container Architecture*" to prove the advantages of container construction that are easy to transport, adaptable, and reusable. It is considered to be an architectural form with great development potential (Kotnik, 2008). By analyzing the characteristics and trends of the rapid construction research on temporary buildings in the mainstream of construction industry, we believe that the current focus has shifted from one-sided "fast" to "convenient" and from "disposable" use of materials to "economically recyclable" trend. The transformed "convenience" and "economic recyclability" will also serve as a cornerstone of the architectural design concept throughout the entire study of this article.

2.3. Discrete design language

"Discrete" as the antonym of "continuous" first appeared in mathematics. The essence of "discrete mathematics" is to study the structure and correlation of discrete quantities (Ne, 2009). Since then, architectural philosophers have borrowed it for the study of architecture and cities. With the support of increasingly large multi-source big data and high-performance computers, they believe that it is necessary to rethink the relationship between the "parts" and the "wholes" of architecture in the information age (Köhler, 2016). In this design language, the designer's focus is no longer on the traditional holistic top-down completion of project ideas, but on the design of discrete components or discrete functional units. In other words, the design of discrete architecture starts from the part, accepts the relationship of each part, and gradually expands from point to surface to complete the whole design.

Different designers call this type of design differently. For example, Kengo Kuma called it as "particlised design" (Carpo, 2019), which Patrik Schumacher thinks the design is a branch of parametric design (Schumacher, 2009). However, they all agreed that the basic component designed by a similar method has significant discrete characteristics and the simple composition logic of this method is suitable for the rapid construction of temporary architecture design tasks.

3. Research scope: Lego Architecture design method

Lego Architecture was first used as a metaphor of organizational structure in the field of computer science, which symbolizes the modular, simple, and universal programming logic. Later, some similar connotations were gradually cited by sociology, political science and other disciplines. The Lego Architecture in this research refers to a kind of design inspired by the logic of Lego bricks, which usually has a significant modular feature in the shape of components. At the same time, Lego Architecture also has the characteristics of portability and speed in construction, and presents the language of discrete design in the way of forming buildings. Based on these characteristics, Lego's architectural design methods are often used in temporary construction areas with small total investment and short construction period, such as temporary resettlement houses after disasters, simple workshops or plant greenhouses in rural areas.

3.1. The practice of previous designers

The discrete design language represented by Lego Architecture has long been quietly popular in the architectural world, and it is considered that it "will greatly change the mode of social production" (Claypool, 2019), thus giving architects stronger problem-solving capabilities. This can be verified in the works of eastern and western architects in recent years. Although the two parties presented completely different styles in their practice in this field, the discrete ideas and rapid construction strategies they displayed were surprisingly similar.

Gilles Retsin, a British architect, advocates applying the strategy of "Low-resolution" to spontaneous housing construction to better meet the needs of automation and democratization (Retsin, 2019). Specifically, through large-scale, typed and low-cost building components, the complexity of field assembly is reduced as much as possible, so as to realize a faster and more flexible assembly or disassembly scheme (Fig. 1a).

In China, Taiwan architect Xie Yingjun's light steel keel assembly building system (Fig. 1b) and the "New Bud System" developed by Professor Zhu Jingxiang of the Chinese University of Hong Kong embody the oriental architectural philosophy. They emphasized the consistency of architecture and structure, and developed several light steel construction systems that are convenient to construct and save materials to meet the special construction environment in rural areas. In particular, Zhu's team advocates the use of component standardization to realize the productization of buildings to meet the construction needs of more rural and remote areas (Fig. 1c). Its design productization intention is the same as Retsin.

It can be seen that, the social issues which the eastern and western architects respond to are different from each other, but the "universal" design principle of building components is consistent throughout all aspects of the work. This standardized construction work done through prefabricated components and on-site assembly reduces the difficulty of construction and improves the efficiency of construction and renewal.

3.2. Current research gaps

How to develop a construction system with more environmentally friendly materials and simpler structures on the existing basis is the focus of this research. Although under the impact of new technologies such as 3D printing, robots, and artificial intelligence collaborative construction, a large number of researches with different paths have sprung up (Yuan et al., 2016). However, by investigating the current mainstream Lego-style architectural works, we found that the field of temporary buildings for rapid construction is still in a relatively initial state. For example, among the representative designers mentioned in the previous section, Retsin's design used a large number of unenvironmentally friendly plywood materials for ease of processing, and Zhu's

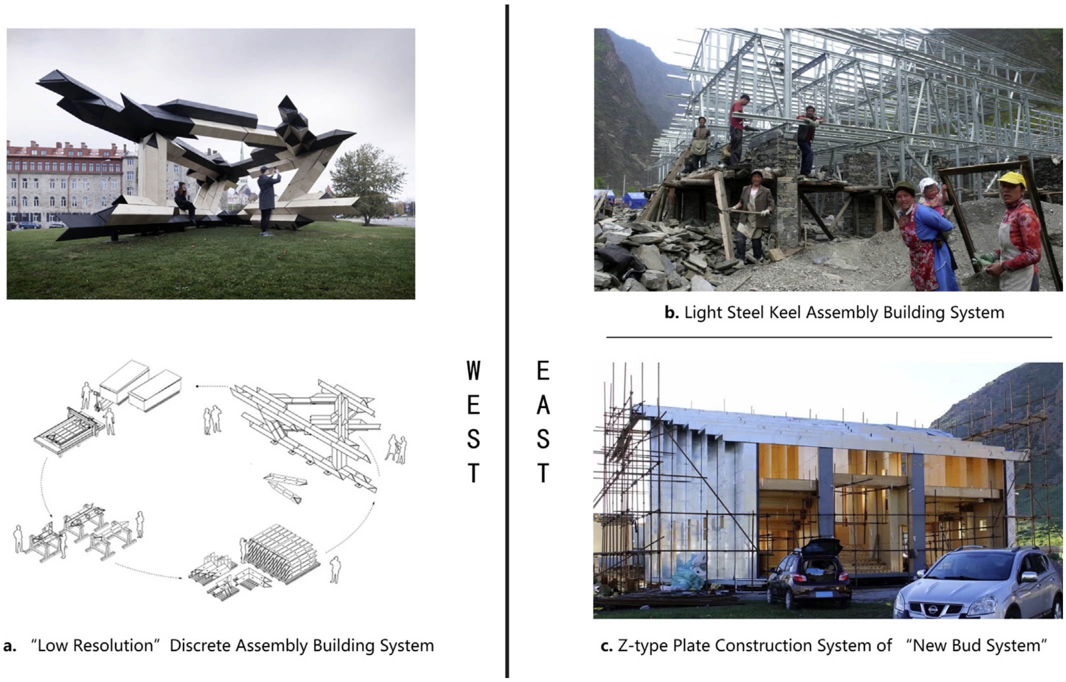

Fig. 1 (a) Gilles Retsin Architects, Tallinn Architecture Biennale Pavilion, 2017; (b) Xie Yingjun Architects, Yangliu Village Reconstruction Project after Wenchuan Earthquake, 2008; (c) Zhu Jingxiang, the new Raouga Primary School in Yushu, 2015. Source: (a) Gilles Retsin Architects website. (b) Related website news reports. (c) Zhulong BBS.

implementation of the plan relied on a large-scale professional machinery to assist. There is a certain degree of potential to mine in the exploration of both sides.

Especially in the design of the connection mode between the components, the current research has great limitations. Even DFMA (Design for Manufacture and Assembly) has become the consensus of the basic principles of prefabricated construction design (Selvaraj et al., 2009; Yuan et al., 2018). "Minimize precast component types" and "use of environmentally friendly materials" are not new topics, but "minimize connector types" seems to be the harder part of the DFMA principle to achieve innovation, which lacks breakthrough research. Because it is difficult to find a new connector that simultaneously meets a large number of rigid requirements such as reasonable structural force, excellent material performance, simple construction, and aesthetics. In the past excellent designs, dry reversible connections were generally used to avoid wet and irreversible connections to speed up construction and increase construction flexibility (Loss et al., 2016; Lukaszewska et al., 2008). However, even dry connection, such as wood mortise, nailing or steel welding, bolt connection, etc., also requires a large number of additional connecting components which are often difficult to obtain or effectively implement in post-disaster emergency construction. In summary, a temporary building structure system that relies on Interlocking connections between the components themselves without additional connectors is a major gap in the current research field.

4. SUP design concept, method and application

Just as Lego toys are suitable for people of all ages to play, Lego buildings should also follow the basic principles of low skill threshold and low risk use. This is the original intention of the SUP project. Under this initial concept, the following will explain the SUP system research from seven aspects, namely: design concept and framework, specific design methods, material application, spatial connection and continuity, algorithm and practice combination, mechanics performance verification and physical construction, and the derivative design of the scheme.

4.1. SUP design concept and framework

As mentioned above, the rapid construction of a large number of temporary buildings in a short period of time has become a rigid need of mankind. However, the types of buildings involved in temporary buildings are very complex. In order to better make targeted designs, this research first gradually narrows down and clarifies the site and functional requirements of the target problem, and restricts the specific research objects to the following types (or areas) temporary construction behavior: temporary resettlement after the disaster, urban emergency site addition, community spontaneous public space construction, and urban village shed area transformation.

In the above types (or regions), people's demand for architectural space is often guided by simplicity and practicality, that is, easy to use and low cost. The best example is the "shack house", which spreads widely in the spontaneous space of the city. It objectively reveals that the priority of "cheap enough materials" and "simple building methods" is much higher than that of "solid" and "beautiful" which orthodox architecture attaches importance to. Secondly, the space expansion demand of this kind of users is in a dynamic change for a long time, and it should not be expected to meet all future use requirements after one-time construction, which is related to the unstable economic structure of the frequent floating population in urban villages and other places.

Therefore, it is necessary to provide a variable and flexible design scheme for this kind of problem. At the same time, on the premise of meeting performance safety, recyclable environmental protection materials should be used as much as possible to realize long-term sustainable development of society. Based on the above objectives, we summarized the following necessary design principles: 1) Convenient construction; 2) Flexible scheme; 3) Safe and environmentally friendly materials; 4) Low construction cost.

In order to better realize the above design principles. It is not enough to make a customized solution for a specific location or problem to meet the multi-purpose needs of multiple types of users. It is necessary to use the Internet thinking of continuous iterative updating to optimize products, and design a set of practical architecture system to provide universal product framework and personalized customized services, so as to meet the space needs of specific communities to the greatest extent. Therefore, based on the common design routines of discrete architecture, this paper designed the following design research framework (Fig. 2).

First of all, it is necessary to make clear what kind of design method is adopted in the overall design; Secondly, according to the functional requirements of building components, the materials of components are determined; Then, find a suitable geometric connection method to design the component assembly scheme; Finally, according to the finalized connection rules, the algorithm program is written, and the specific design scheme of each project is completed by computer-aided, and at least one scheme is actually built according to the ratio of 1: 1 for physical testing.

The above-mentioned process does not end the research immediately after being carried out once. In this kind of prototype design, according to the feedback results of users and the market at different stages, design iteration and update should be carried out in combination with digital simulation and entity verification, and "products" should be optimized repeatedly to form a complete adaptation process for the rapid construction of temporary buildings.

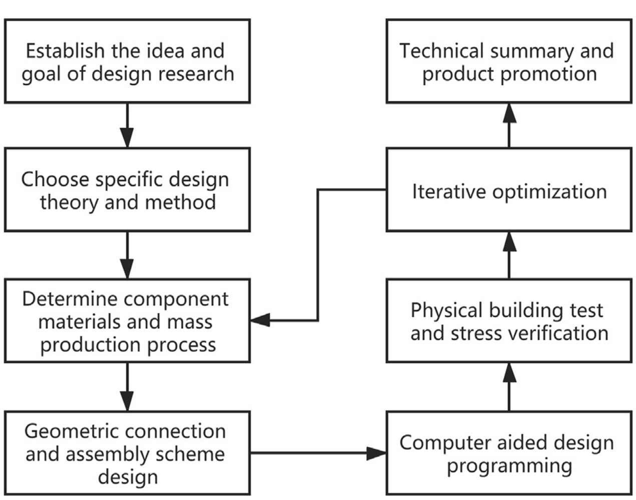

Fig. 2 Process framework of design research.

4.2. Specific design method

Inspired by Philippe Morel's Bolivar chair prototype design (Fig. 3), based on the principle of discretization, this design adopts the method of voxel design, and disassemble the target building entity into voxel blocks of the same modulus in three dimensions. At the same time, the realization of this method is closely related to the Generalization Design of components. Building components based on the same connection language are the key to make the works as easy as Lego bricks, and all components are combined with discrete components without any external connectors. The reason why common nails or glue are discarded as adhesive is that once other connection modes are used, the uniformity and predictability of joint strength after such subjective construction cannot be guaranteed. Special connection independent of the system also means that human subjective intervention will take precedence over computer simulation results, which will undoubtedly hinder the realization of building productization.

However, large discrete buildings often have thousands of discrete components, which upset or destroy the simulation results, which increases the difficulty of actual construction and greatly weakens the robustness of the whole system, which undoubtedly makes the construction

Fig. 3 Bolivar Chair-Test No.320, EZCT. Source: EZCT booklet screen.

advantages of all discrete buildings preset before become empty talk. Therefore, the research team decided to use only the S, U, P building components to complete all the main building, which are not only the floor and ceiling of the building, but also the vertical and horizontal stress components and connectors of the building. At the same time, based on the basic principle of modularity, a special kind of building logic is found, so that three kinds of component elements, S, U and P, can be combined into voxels that can be continued in space in three axes and six directions, thus meeting the flexible and variable requirements of the scheme (Fig. 4). It is precisely because of sticking to Lego's Super Simple Construction that after a long process of geometric exploration, the research still uses only S/U/P building components to complete the main design, which is why the whole design method was named "SUP Design".

4.3. Applied research on materials

In the context of rapid construction without the aid of large-scale equipment, the use of lighter and stronger materials is an ideal choice. Based on this starting point, the precast concrete members which are widely used in the construction industry are excluded, and the most suitable materials are expected to be found among lighter plastics, new synthetic materials or bamboo.

First of all, natural raw materials such as bamboo or wood are excluded, because they cannot meet the precision requirements of standardization, which creates obstacles to the large-scale implementation of the follow-up scheme. According to the principle of environmental friendliness and recyclability, Acrylonitrile Butadiene Styrene (ABS) and Polyurethane foam, which have been widely used in the construction industry, are selected as alternatives among various kinds of plastics and new synthetic materials. Among them, ABS has outstanding physical and mechanical properties. It is safe, nontoxic and impervious, which is an ideal building material. And based on the excellent thermoplastic properties of ABS, we can use injection molding or 3D printing to realize rapid and mass prefabrication of components.

Another candidate, rigid foam of polyurethane foam, is a new type of synthetic material with good thermal insulation and waterproof performance. According to the different ratio of raw materials and formula, it can be controlled to obtain better strength and weight than ABS. However, polyurethane material is relatively flammable. After the "11.15" fire incident in Shanghai, it was called by relevant Chinese experts to stop. Therefore, this study did not choose this material because of concerns about the potential fire hazards in the community.

Based on all the above factors, the main material of building components is ABS, which is combined with factory open mold injection production and self-3D printing manufacturing, so as to complete the physical construction of various design schemes, and facilitate the later dismantling and recycling.

In the aspect of material economy, the research team also started to control costs from the source of production. In Yuyao, China, a famous mold production and wholesale city, after sample production testing and price comparison by many manufacturers, a preliminary agreement was finally reached with the manufacturers that the ex-factory cost of large-sized components (which are most commonly used in physical construction scale) averaged 7.05 yuan

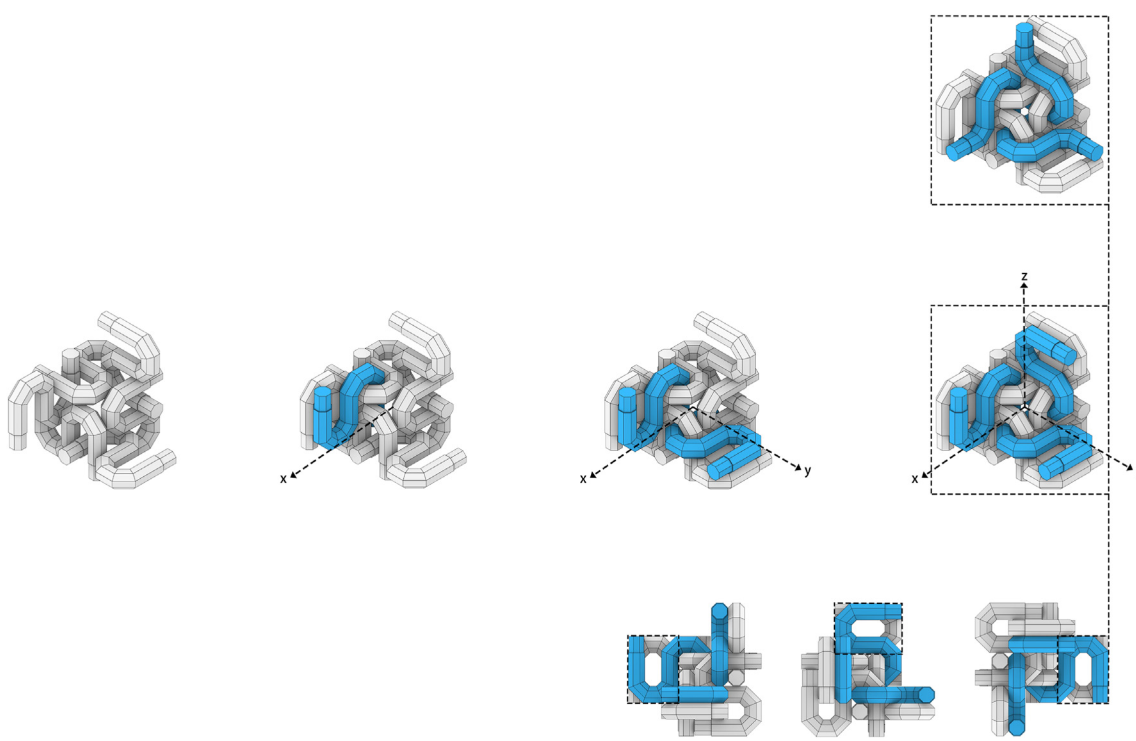

Fig. 4 Diagram of three-axis and six-direction spatial connection nodes of "8 modulus" voxel block (decomposition).

each (about 1.08 US dollars). Even if additional expenses such as transportation costs are added in the later actual construction process, it is estimated that the final use cost of each component will not exceed the 8 yuan (Table 1).

In this case, it takes about 800—900 large-sized components to build a conventional micro-space (L:2 m × W:6 m × H:2.5 m) for two people, so the main material cost of this structure can be controlled at around RMB 6,800, which is slightly lower than the price of container houses of the same size (RMB 8,000—11,000) commonly found in urban villages and construction sites in the market. It is worth mentioning that injection molding is a standard large-scale production mode. With the increase of output in the later period, the marginal cost of products will gradually decrease, so the total cost of structures still has the potential to be further reduced.

4.4. Connection and continuity of space

Finding the possibility of connection from the perspective of space geometry is the difficulty of this design. Different from the traditional brick, the four voxel block schemes adopted in this design show the connection characteristics of mirror image relationship on the six faces of the cube. Specifically, due to the Male-Female fixation of our basic components, there is an accurate mirror alignment requirement for the connection position and sequence of specific components. Therefore, when connecting voxels spatially, the six faces of the voxel are labeled as blue and red labels according to the matching connection methods. U-shaped components can be used for socket locking connection between different color systems, while labels of the same color system cannot be effectively combined (Fig. 5).

At the same time, the modular design allows the component to have the characteristic that it can still be engaged with the original size component after the size multiple changes. By inserting connectors belonging to SUP system as shown in the figure (Fig. 6), the conversion and connection between sizes can be realized, providing multi-dimensional design potential for the diversity of specific design schemes.

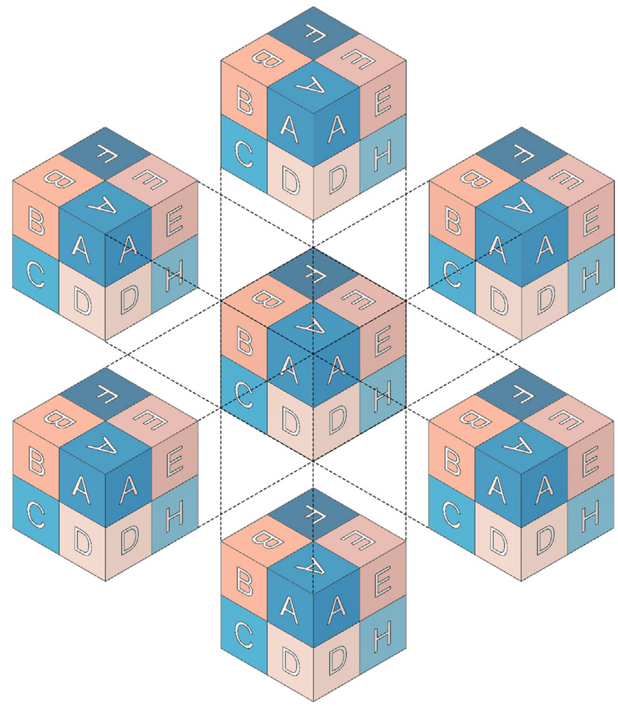

Fig. 5 Diagram of label processing of voxel block connection algorithm.

The whole set of component combinational logic seems complicated, but in fact, the connection rules between them belong to the same locking principle of self-Interlock. When the number of components reaches a certain level in large-size monomer design, the visual effect will present a complex but regular texture feature. Therefore, in order to assist the construction better and more accurately, it is necessary to use computer automation to generate corresponding schemes according to the specific needs of users, and to guide users to build gradually from bottom to top by visual means. So, we summarize all the above spatial connection rules, use Grasshopper plug-in of Rhino platform to program (Fig. 7), and form a set of design program which can automatically generate the target scheme according to the given geometric boundary.

Table 1 Production cost of some components agreed by the research group and a mold factory in Yuyao (excluding mold making). Source: Excerpted from the contract signed between this research and mold factory (August 2019)

Product Shape	Material	Weight	Material Cost (RMB)	Production Cost (RMB)	Total Cost of Single Piece (RMB)
Large U	ABS	160g	2.3	4	6.3
Large P	ABS	205g	3	4	7
Large S	ABS	265g	3.85	4	7.85
Medium U	ABS	25g	0.355	3.3	3.655
Medium S	ABS	34g	0.483	3.3	3.783
Medium P	ABS	26g	0.369	3.3	3.669
Small U	ABS	7.3g	0.104	0.25	0.354
Small S	ABS	10.2g	0.145	0.25	0.395
Small P	ABS	8g	0.114	0.25	0.364

4.5. Combination of algorithm and practice

When using a single-scale version of the program for scheme design, there is an aesthetic problem that the Pattern is too repetitive locally (Fig. 8), and too many component connection ends will also lead to structural redundancy. For this reason, considering aesthetics, we simplified some voxels into aluminum tubes that can still transmit force without affecting structural performance. This simplification not only uses line language to replace part of the body, but also maintains the continuity of the force within the system. This kind of aluminum pipe still follows the general design logic of SUP components, that is,

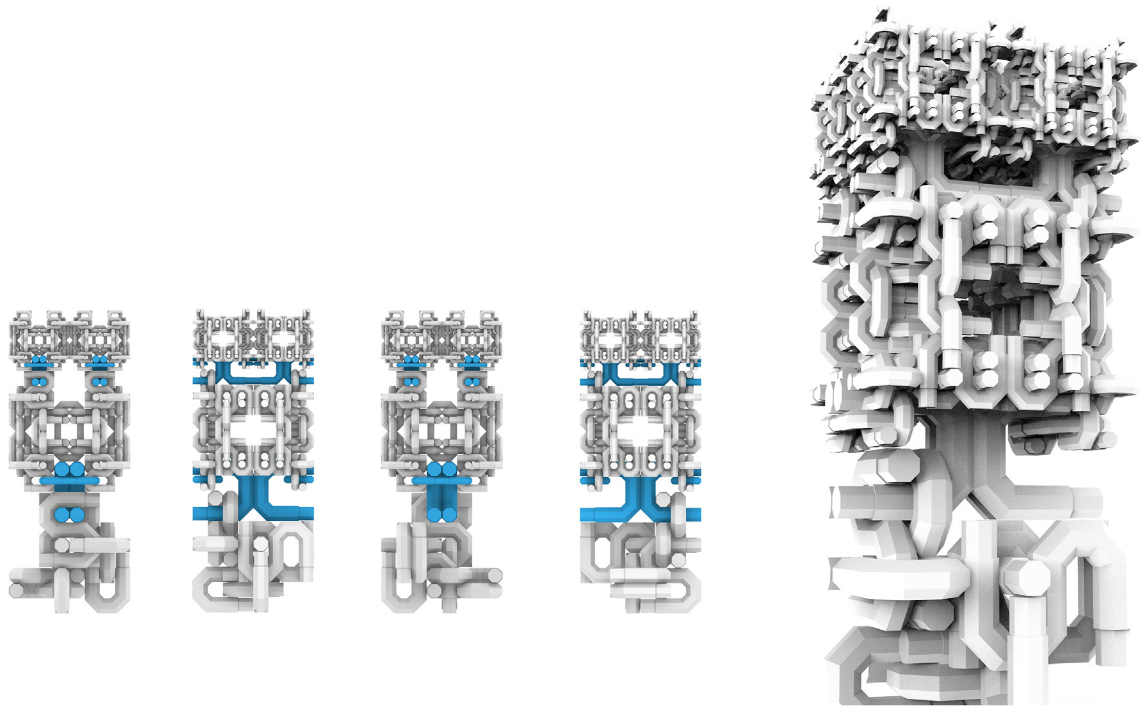

Fig. 6 Node details of cross-scale transformation connection structure.

it adopts octagonal cross-section with the same size, with hollow inside, and the edge thickness (2 mm) is in line with the reserved clamping indentation thickness at the end of common components. At the same time, the standard length of aluminum pipe series is also based on the length value of product general Module ($L_{Alum} = n^{*}L_{module}$). Therefore, this kind of aluminum tube can not only connect the connecting ends across voxel blocks point to point, but also insert into the gaps between voxel blocks to play a role in strengthening the structure.

After considering the aluminum tube elements, we used Karamba software to perform finite element analysis (FEA) on the models before and after the aluminum tube replacement, and carried out an iterative optimization design of the plan as a whole with reference to the different load results (Fig. 9). Finally, we found out the

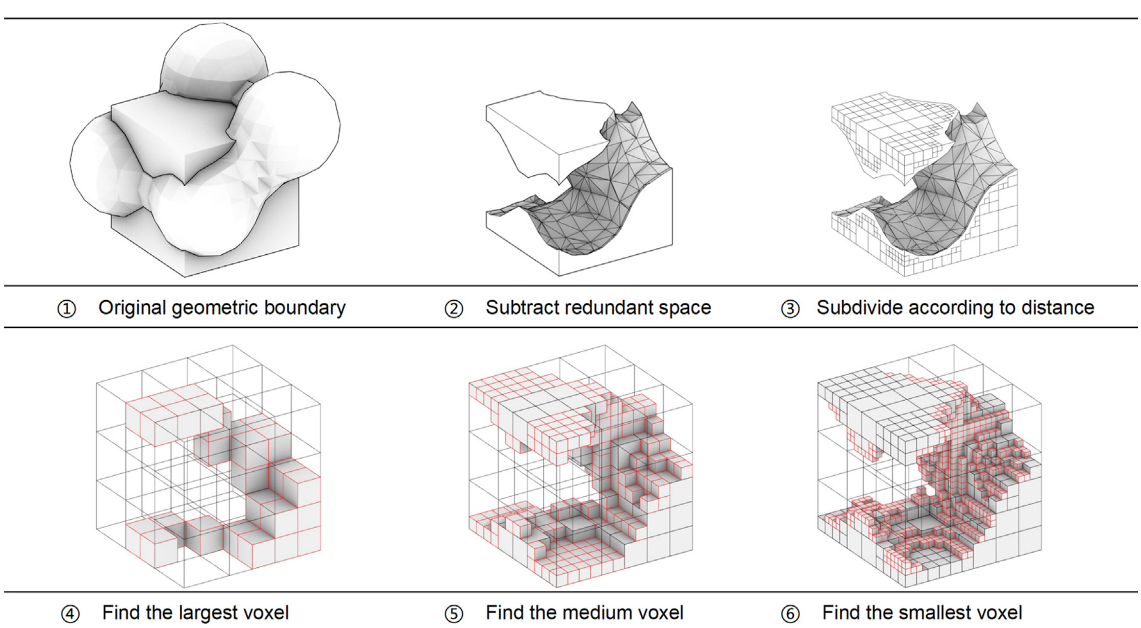

Fig. 7 Part of the process demonstration of simulating a specific design by using Grasshopper running program.

Fig. 8 Design effect of SUP voxel space based on single size.

spatial distribution characteristics with appropriate density in the subsequent design scheme, which not only gave more possibilities to the products in the aesthetic level but also in the functional level (Fig. 10).

4.6. Mechanical performance verification and project physical construction

Based on the design and improvement results of the above schemes, the representative scheme is finally selected for physical construction and verification. At first, all the building components are verified under the same size. During the period, because the aluminum pipes purchased for the first time did not arrive in time, wooden sticks with cut edges were temporarily used instead, as shown in Fig. 11(a). As mentioned above, the wooden stick has natural errors and stress deformation, which leads to the unsatisfactory completion of the structure shape in the first experiment, and the poor stability performance after the overall construction.

The second construction activity was invited and funded by The Aram Gallery in London. After all the aluminum components were purchased and assembled, the finished

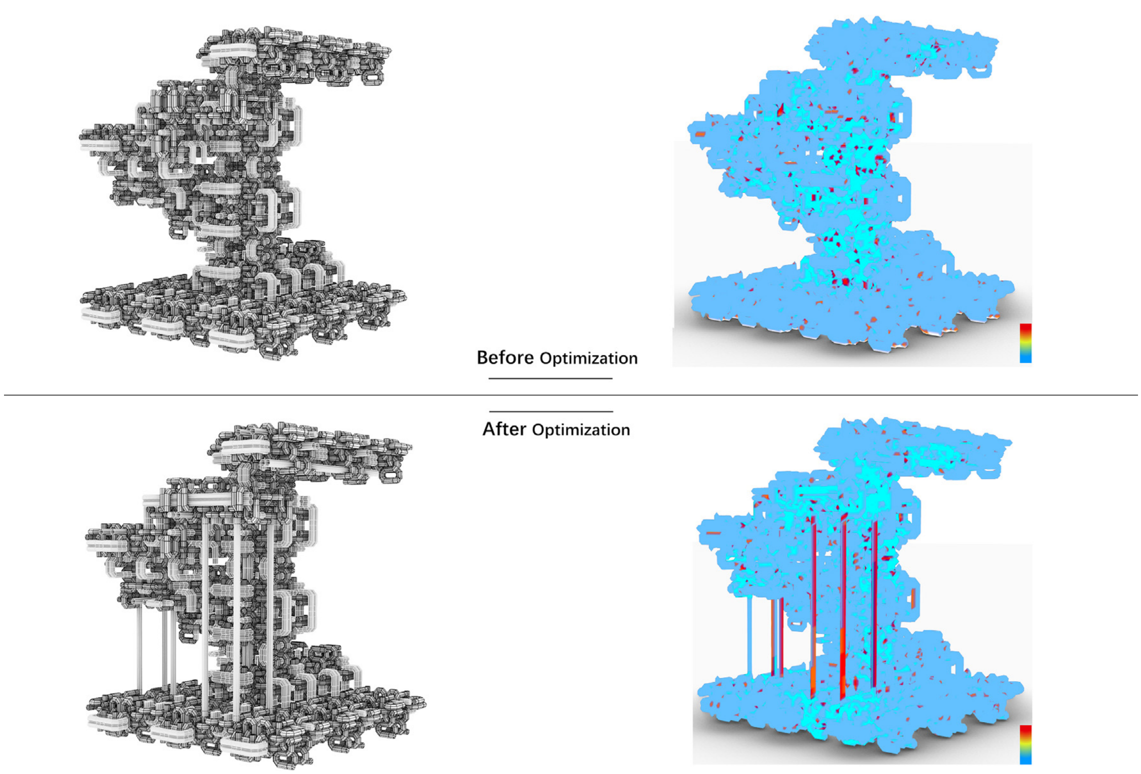

Fig. 9 Comparison of structural loads before and after replacing aluminum tubes.

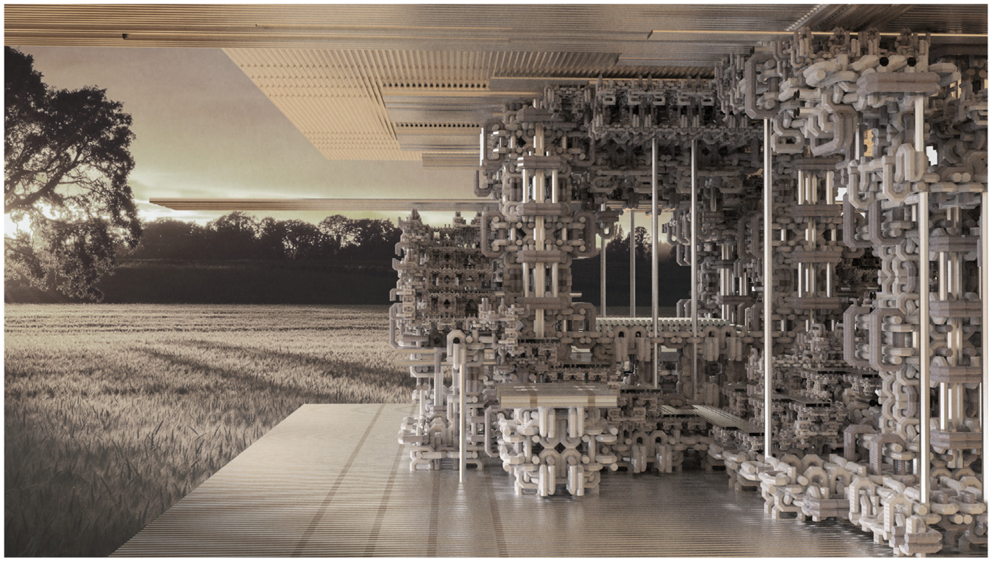

Fig. 10 Design intention render of small space after adding aluminum pipe and size change.

products showed outstanding mechanical stability (Fig. 11b). It is worth pointing out that four people (two men and two women) of the research team completed all the construction work of the project in less than 8 h, which verified the expected efficiency after adopting the voxelized construction scheme.

Finally, after introducing the iterative design with dimensional changes, the team used the components of large, medium and small sizes ordered from China, combined with the recycling of the above-mentioned movable aluminum pipes, and carried out a more complex scheme construction work (Fig. 11c). Obviously, the design scheme with more layers shows more details, but it also brings great physical challenges to manual assembly.

4.7. Derivative design of the project

In this case, the core concept of Lego Architecture is strictly implemented according to the actual construction and use requirements. Its low cost, easy assembly, flexible, firm and practical product characteristics determine that it will be promising in the field of temporary buildings which requires rapid construction. Based on the above exploration and experiment, the following researches have been made on the applicability of the scheme for more special building construction scenarios.

Firstly, two simulated bidding designs were selected: the first was the post-disaster restoration project for several church fires in France in 2019; The second is the

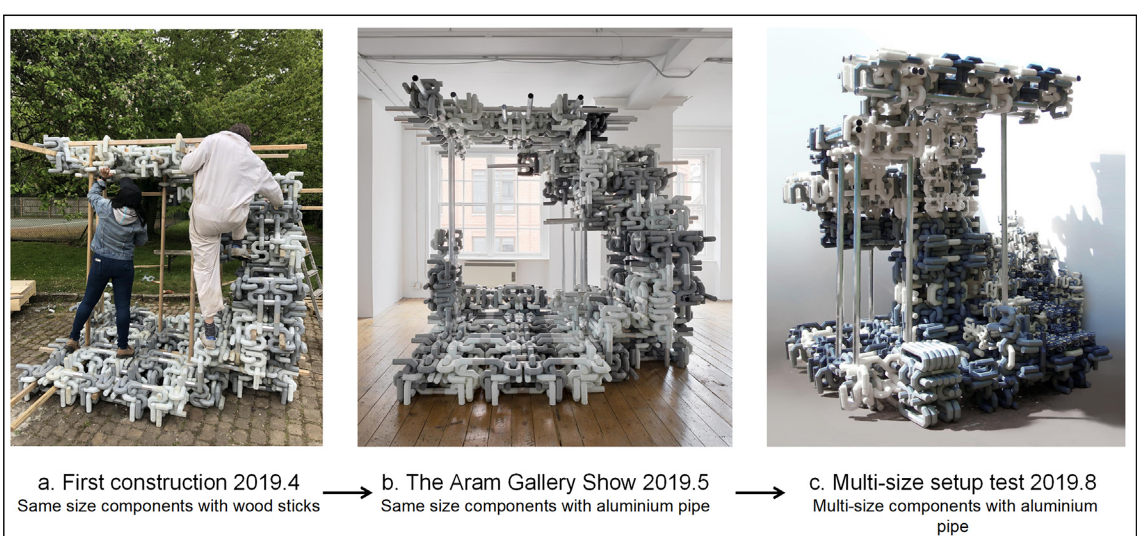

Fig. 11 Three physical construction results in the process of design iteration (in chronological order).

Fig. 12 Local reconstruction and repair of a church based on SUP system.

resettlement project for the victims after the 7.8 magnitude earthquake in northern Peru in May 2019.

For the first restoration project, the scheme was designed as follows: according to the overall scale of the site, the size of the components was enlarged to twice that of the experimental products. Based on the flexible nesting relationship between voxel blocks of different sizes, the original building outline can be well fitted. The research combines the results generated by computer simulation to accurately repair the damaged and incomplete parts of the church, while retaining the changeability of local fine adjustment at any time (Fig. 12).

In the second resettlement project, more attention was paid to the construction of internal places. Based on the diversity potential of SUP components' own design, combined with the empowerment of cross-size connection characteristics, interior furniture and other functional facilities are designed and built with the same pattern language. This approach not only forms visual consistency, but also saves a lot of disaster relief costs. Because there is no need to add furniture such as tables, chairs, benches and beds after adopting this set of design products (Fig. 13). The logistics support system only needs to package and transport the same product in a unified way, which can meet most of the living hardware needs of the victims and directly reduce the intensity and complexity of post-disaster material transportation.

5. Discussion and conclusion

In past studies of discrete architecture, the way in which components are connected to each other is a point that is easily overlooked. An in-depth exploration through the lens of the geometric topological characteristics of discrete components is urgently needed. The emergence of the SUP system has proven to some extent that temporary buildings that rely entirely on component interlocking can be realized in the real world. In fact, this study was initially bogged down in the search for basic geometric forms, but was greatly inspired and encouraged by traditional Chinese mortise and tenon structure and the case of Luban lock. The simple logic of "yin and yang" complementary interlocking between the components and the material toughness of ABS, which recovers quickly from minor deformations, is the key factor that makes the SUP system possible.

From the view of the design method, the SUP system has the characteristics of discrete architecture, which fully reflects the connotation of Retsin's famous definition of discrete buildings (Retsin, 2019): "Discrete buildings are continuously repetitive, and reconfigurable universal discrete component sets have been developed with design strategies that can be assembled into fully functional and complex buildings." Thus the SUP system, in line with other discrete construction projects, can rely on a large number of offsite prefabricated components to improve an overall erection efficiency, reduce marginal costs and improve the economic viability of the scheme in a post-Fordist industrial production model.

The renowned American economist Jeremy Rifkin has excitedly claimed that new manufacturing processes based on digitalisation and sharing could even enable "producers and consumers" in the construction industry to produce and share at "zero marginal cost" in the future (Rifkin, 2014). He advocates releasing the capacity of previously closed prefabricated building manufacturers to the community under the way such as the Internet of Things, which can be used to eliminate the idle capacity and waste caused by lagging information exchange. Benefiting from the advanced 3D printing technology, we can share the digital models of our SUP via an internet platform, which achieves the goal of off-site distributed production of building components for the required users to build the required space facilities quickly and cost-effectively.

During the design process by using SUP components, we also discovered the potential of the architectural system to be embedded into existing buildings as temporary functional clusters. In fact, in both public and private buildings, the division and layout of large spaces inside and outside

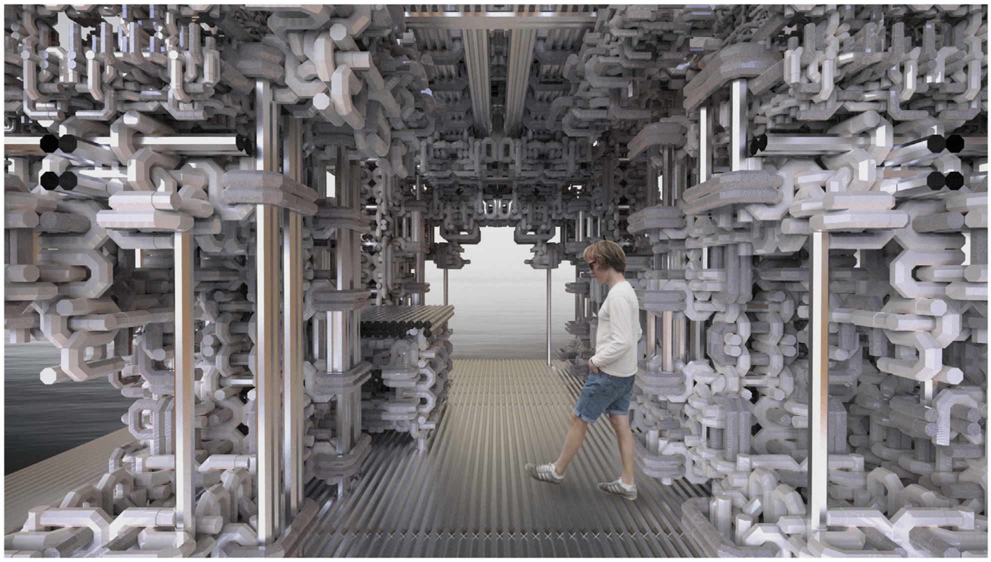

Fig. 13 Design of a resettlement unit for the victims.

the building are often adjusted to suit the temporary use of space at different times (Madanipour, 2018). The SUP system is used to organize and build spatial units of different scales such as exhibition stands, partition walls, seating, corridors, and experience shops. On the one hand, it can quickly and flexibly meet the functional requirements of various activities; on the other hand, all materials can be completely recycled after their use, increasing the efficiency of economic recycling.

However, the temporary buildings constructed through SUP system still have some shortcomings that have yet to be resolved in this research. The nature of SUP structure gives some advantages in terms of speed and ease of erection of the system, which in turn makes it difficult to achieve building sealing and waterproofing on its own. Our research team had considered designing another membrane system as a 'skin' to be attached to the 'skeleton' of the SUP to achieve comfort features such as waterproofing and insulation. However, the superimposition of the two systems has somewhat reduced the flexibility and resilience of the solution, making the physical erection of the test pieces significantly slower and more difficult. The extra time and material cost made us finally choose the former between "fast" and "comfortable", and perhaps we can find a better way to resolve this conflict in the future.

In summary, the study in this article constructs a temporary building design methodology for rapid construction based on the three shapes of S/U/P components, placing the design of open construction systems at the centre, encapsulating the knowledge required in the relevant fields, and packaging it into a standardized product for the community to use on demand (Sanchez, 2020). By exploring the possible aggregation methods of a large number of spatial geometries, our research team has found an effective self-interlocking connection method. Secondly, based on the building logic similar to Lego bricks, the research team used parametric tools such as Grasshopper to write a program that can generate corresponding design schemes based on the edge shape of the target space, providing a visual guide for the physical construction of the SUP system. In the final building experiments, the research team partially optimized the design for the actual situations encountered, so that a final balance between aesthetics and stability was achieved in the SUP system.

In recent years, various natural disasters such as earthquakes, tsunamis, flash floods, and global epidemics have become more frequent. As a result, more temporary buildings are needed as the emergency house, restaurant, school, and even hospital. Among a variety of rapid construction solutions, the SUP system, as a typical high science and low technology design, may provide some inspirations for other architects to create better architectural solutions for mankind.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The SUP project was completed in the Material Architecture Lab of the Bartlett in UCL in the academic year of 2018—2019. The main members are Daoyuan Chen (i.e. the author himself), Dong Su, Zhuoya Li and Pei Chen, and the tutors are Dr Guan Lee, Daniel Widrig and Adam Holloway. Thanks to all the teachers and team members I met in UCL, especially Dr. Guan Lee for his support of this project. I would also like to thank Dr. Patrik Schumacher and Professor Mario Carpo for their comments and guidance on this project. Their opinions played a very important role in the development and implementation of this design.

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