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A Review of Optimised Additively Manufactured Steel Connections for Modular Building Systems

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Abstract. This paper is presenting various types of innovative material technology that can be achieved by 3D printing and their potential to advance the connection design in modular building systems (MBSs). Connections can embrace flexibility, adaptability and resilience in the design of modular systems enabling dismantling, repair and reuse – towards faster transition to autonomous construction (e.g., with robotics). Rapid developments in additive manufacturing methods play a key role in the design such innovative mechanical systems.

Connections in modular buildings are the most critical parts of the system performance and integrity, but are currently receiving less attention compared with other structural elements (e.g., joists and studs). Optimised 3D printed connections can substantially improve the design of modular building systems with the ability to connect complex geometries and components that would be time and cost-prohibitive or even impossible to produce with traditional manufacturing methods. Therefore, this study reviews the latest connection designs of MBS units which can be replaced with 3D printed elements. In addition, advancements in additive manufacturing (AM) materials are included in this paper, exploring how AM can improve connection design in terms of both material properties and geometry.

Keywords: Structural Topology Optimisation; Additive Manufacturing; Structural Connections; 3D Printing; Modular Building Systems; Flexible Connections; Adaptable Connections; Material Composition.

1 Introduction

Modular construction has become increasingly popular as an alternative to traditional construction, because it is highly efficient with less input of time and labour, and less on-site construction waste production. While many studies have focused on the structural system of modular buildings, connections have been poorly investigated. As one of the main contributors to carbon emissions, the construction sector is now focusing on reducing the environmental impact of building designs and the connection design is a key challenge in the realisation of flexible and adaptable modular structures, featuring flat-pack systems, composite systems, or hybrid systems. The application of 'plug & play' modules, which are manufactured and tested off-site and then slotted into position on-site, is fast gaining favour in the building sector, offering shorter construction times, improved safety, reduced waste and higher performance. During the construction stage, lifting and handling of modular units are still challenging tasks, thus reducing module weight via a sophisticated connection design is a priority. In conventional modular buildings, connections are simply designed to integrate adjacent modules. Modules in MBSs are normally welded as well as bolted together to form a rigid inter-module connection that is strong to carry vertical loads, but can fail in a non-ductile manner under lateral loads due to wind and earthquake, and can be hard to disassemble without damaging the structure [1].

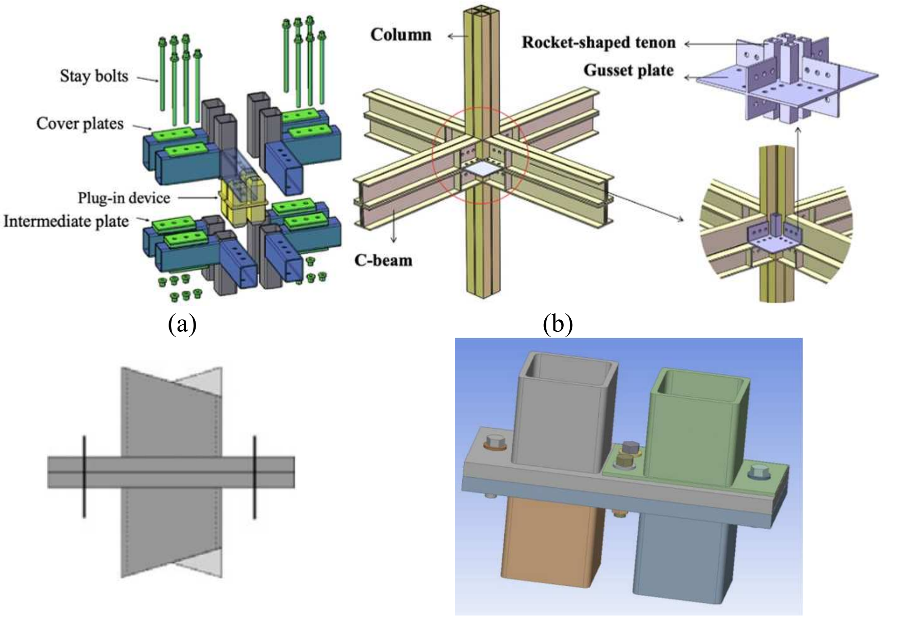
Additive manufacture (AM) has already been successfully used in medical, aerospace and manufacturing sectors, and there is an increasing interest in AM solutions for the construction industry. Compared to conventional manufacturing methods, AM offers numerous benefits including geometry freedom, better structural efficiency, as well as the possibility of functionally graded material and prestressing [2]. AM has already been utilised in a number of innovative construction projects [3], [4], [5], demonstrating its potential for more widespread use. AM is often used in association with structural topology optimisation (STO), as well as other forms of design optimisation, to improve structural efficiency and has achieved positive outcomes when developing innovative buildings, elements and systems. Limited work has been carried out yet on AM-related connection designs which in turn can have great impact on the mechanical performance of the overall structural system providing stability, robustness and resilience.

This paper presents an overview of recent studies toward innovative demountable connections in MBSs as well as existing studies on the application of AM for optimised structural elements, and the ideas of how to integrate them in connection designs. In the following section, future opportunities and challenges of additive manufactured connections for modular buildings are investigated.

2 Connections in modular building systems (MBSs)

2.1 Inter-module connection

One form of modular construction is by using volumetric building modules which are prefabricated in the factory, then transported to the construction site and assembled to form the overall MBS. Connections in MBSs are essential part of the structure as modules need to be connected horizontally and vertically to form the overall building system, so that they strongly affect the overall stability and robustness [6]. There are various connection systems now available for modular buildings (Fig.1). Most of them consist of bolts, plates, and welds to form rigid joints between columns, beams, and modules [7], [8], [9].



(a) (b)

(c) (d)

Fig.1. Examples of existing inter-module connections [10] (a) bolted connection with plug-in device [9] (b) bolted connection with rocket-shaped tenon and gusset plate [11] (c) bolted end plate [12] (d) bolted beam-to-beam module connection [13].

Despite the rigidity provided by bolted and welded connections, their installation is still somewhat problematic [6]. The welding of connections is made on-site and external access to the modules is required via mobile access platforms, which increases the difficulty and risks of construction; such operations also have complex and expensive requirements. The access for installation of the inter-module connection is more difficult than the module to foundation connection as it is often not straightforward. For example, case shown in Fig.2; when the fourth module is to be placed, it is somewhat difficult to connect it to the other three modules since the access space is limited [9].

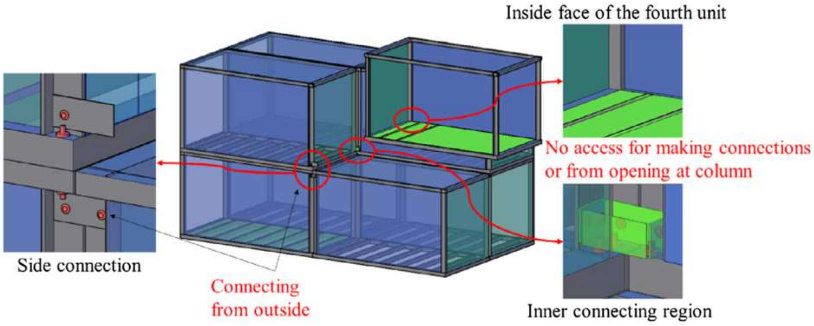


Fig.2. Access difficulty for installation of conventional inter-module connection [9].

In addition to the installation difficulties, the inter-module connections (connections between stacked modules) are more critical to the mechanical performance of the entire building compared to the intra-module connections (connections within a module). Apart from providing integration of discrete modules, inter-module connections are also designed to transfer horizontal and uplift forces as a result of wind and seismic actions, while gravity load is typically transferred by other structural elements such as walls and columns. Under the worldwide tendency of building high-rise buildings to accommodate increasing population, modular connection design is facing new challenges with relation to lateral stability and dynamic performance, which makes the ductility of connection an important factor while withstanding shear (horizontal) and tension (uplifting) forces as well as dissipating energy to prevent brittle and sudden failures. Ductility and strength redundancy in inter-module connection design is also important to allow load redistribution in an accidental case when part of the structure gets damaged to avoid progressive collapse of the entire structure [14].

Overall, connection systems for MBS are still under development with scope to improve the ease of installation while retaining structural performance for the full development and exploitation of modular construction.

2.2 Demountable Modular Building

Besides the installation issues, another challenge brought by using non-demountable welding in connection systems is the recycling and reuse of structural materials. Even modular buildings are mostly disposable; currently available connectors in construction cannot be efficiently removed without damaging the structure, thus the reuse of structural materials and components is still a relatively new concept. With demountable connections, structural elements can be reused at the end-of-life of buildings, so that less waste will be produced and less energy is used for their recycling. In this way, the environmental impact of the modular construction sector can be significantly reduced, ahead of any other construction method in line with urgent demands to decrease carbon emissions in the construction sector. Thus, the development of demountable connections in MBSs is becoming a new challenge.

2.3 Interlocking Connection for Modular Building

For reducing time and risks of modular assembly, recent studies have proposed novel connection designs using fewer welds, key to achieve the abovementioned demountability, with side benefits such as improvement in MBS seismic performance [1].

Integral mechanical jointing is a traditional connection that can integrate elements without any additional connectors. Structural elements are connected via the interlocking of their geometric features rather than bolts and welds. It was widely used in traditional timber buildings but then became less popular in the construction sector due to manufacturing difficulties. Now, with the development of advanced manufacturing technologies, such as additive manufacturing (aka 3D printing), integral mechanical jointing offers the construction industry a new capability of connecting elements to encourage the development of structures with easier assembly as well as demountability i.e., the capacity to fully dismantle undamaged structural components and realise reuse [15].

Generally, integral mechanical connection offers several advantages over conventional mechanical connections [14] [15], such as:

- Easier and faster assembly;
- No additional adhesive or connectors like bolts and welds are needed (no additional weight);
- Demountability and reusability;
- Potential for automatic assembly (reduce risk of operation);
- Reduced stress concentrations.

While some shortcomings should also be noted:

- Risks of coming apart;
- Manufacture cost increase;
- Difficulty in manufacture.

Simple interlocking designs are used in some existing integral connection systems for modular buildings. Modular Housing System (MHS) is a traditional post and beam system but with great demountability and adaptability benefited from the interlocking technology. The aluminium beams and columns in the system are interlocked via their special geometric design and strengthened by concealed bolt-and-clamp components (Fig.3) [16]. In addition to the ease of installation, maintenance and modification offered by modular construction, the interlocking mechanism of connection in MHS enables 100% recycle and renewability of the structure while providing sufficient robustness and superior seismic performance [16].

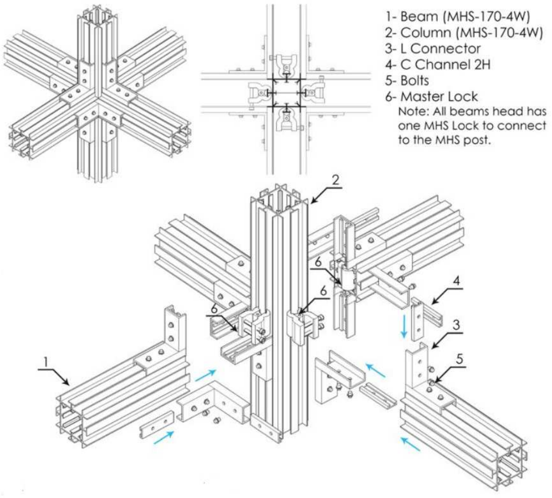
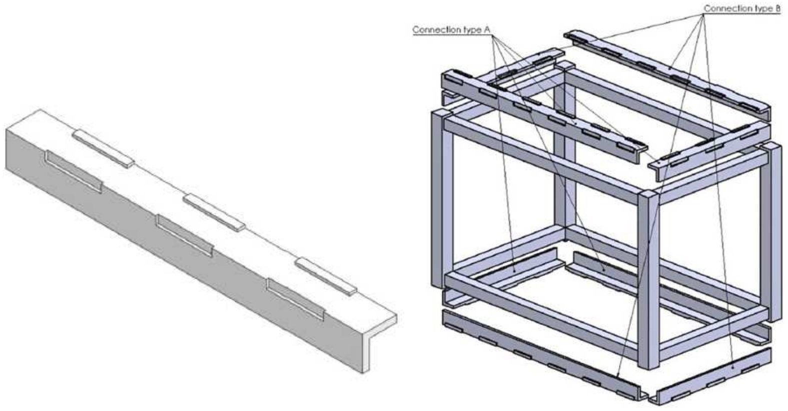


Fig.3. Structure of MHS connection [17].

Sharafi et al. [14] proposed a Modular Integrating System (MIS) using interlocking connection strips that have high flexibility and are readily demountable (Fig.4). Modules with this connection can be easily assembled to adjacent modules by pushing and sliding moves. In numerical and experimental analyses, a structure using MIS showed sufficient stability under notional static and dynamic horizontal forces and partial structure removal simulations, indicating that this type of integral connection is a potential alternative to modular building connection with easier assembly and sufficient stiffness. Another benefit provided by MIS is its flexibility, which is important for connection design but is often neglected. Modules can be manufactured with different properties and dimensions of structural components from different manufacturers. Dimensional flexibility allows the connection to fit different module units, thus simplifies the connection design process. In addition, dimensional tolerance can help address unpredictable constructional issues such as incorrect foundation alignment and variations in space between modules [14].



(a) (b)

Fig.4. Structure of MIS connection (a) Interlocking connection strip with tongues and grooves (b) Attachment of strips to modules [14].

Jenett et al. designed a modular, reconfigurable unit element at meso-scale using discrete lattice material and an interlocking system (Fig.5). As the unit elements can connect to each other without additional connectors, they can freely form different structures and can be dissembled easily [18]. The geometric freedom offered by the design demonstrates the potential of reconfigurable connection systems. That means, it can be possible for the structural engineer and architect to use bespoke unit designs to build inter-module connections, intra-module connections and module-foundation connections, and connections for linking modules in special orientations. Such designs can certainly save significant amount of time in design and construction and allow freedom in architecture.

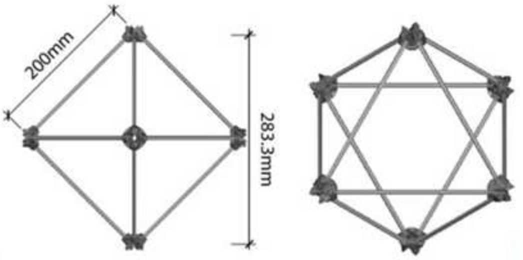


Fig.5. Example unit element and dimensions [18].

Interlocking is a promising solution for demountable, flexible and resilient modular construction, however is restricted by conventional manufacturing methods. There are some commonly used types of interlocking designs, such as pin and cavity, dovetail, cantilever snap-fits and annular nap-fits, each of them offers different kinds of constraints [19]. The aforementioned connection adopts simple interlocking designs for the ease of manufacture, so may not be adequate for large constructions. With the freedom in geometric design, more complex interlocking design, alike the one shown in Figure 5, can be possible using AM, which offers multi-directional constraints while satisfying the structural properties.

3 Application of additive manufacturing in construction

3.1 Structural topology optimisation of structural elements

Exploring more innovative connection designs is still constrained by the limitations of material properties and conventional manufacturing methods. AM as one of the most advanced manufacturing methods, allows new ideas to develop in terms of material and geometry while designing high-performance connections for MBSs. Geometric/architectural freedom is a key benefit offered by AM. Complex features which are not normally used in conventionally manufactured elements due to manufacturing limitations, such as those including curve surfaces, can easily be introduced in 3D printed designs [20] [21]. Therefore, AM is an ideal manufacturing method for complex designs such those developed by using design optimisation (e.g., structural topology optimisation) techniques resulting in better efficiency in structural elements by satisfying the mechanical demand with minimum weight [22]. However, experimental testing on the behaviour of the 3D printed products, and certification, is much needed [23].

In structural topology optimisation specifically, structural efficiency is achieved by removing unloaded or less loaded areas under given load and boundary conditions [24]. Optimised outcomes should be combined together and refined to obtain the final design, after some post-processing. The stability of the optimised design should be verified by comparing the critical stress in all parts with the stress limits in all the load cases [16].

Many studies have presented the significant benefits that can be derived from design optimisation, one of which is the direct reduction in material use. Arup [25] applied

STO to the joints of a tensegrity structure and achieved a 75% reduction in connection weight and 50% reduction in height, which resulted in an overall weight decrease of 40% (see Fig.6). Smith [26] optimised a benchmark beam with different nodal spacing and boundary conditions, achieving better strength-to-weight ratios (maximum 18% higher) while remaining similar ultimate strength. Similar trends have been demonstrated in other experiments including the design of node-connections for lattice [18] and reticulated [27] structures (Fig.7), indicating that STO is an effective tool for reducing material usage while retaining the same structural capacity. More importantly, the stress flow through the structure is optimised by the spatial reticulated shape with alternative load path, which enhances the flexibility and resilience of structure without adding more stress into the connection. Therefore, the optimised node-connection enables lighter and fewer members to support the structure, leading to significant reduction in the overall weight. This characteristic solution by STO is advantageous to connection design when weight reduction is becoming more significant in modular building construction, for the increase in seismic and wind performance and the ease of assembly and lifting.

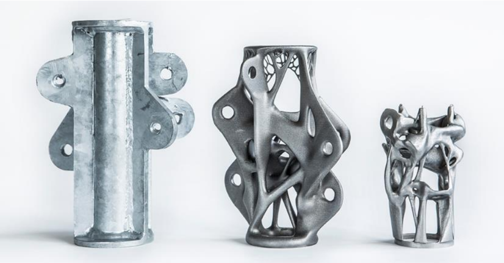


Fig.6. Original joint design (left), interim version of optimised joint (middle), final optimised design (right) [25].

Fig.7. Optimised and 3D printed steel node-connection design [27].

Besides substantial weight reduction, STO can also be used to tailor geometrical properties such as moments of inertia to achieve better stiffness in structural elements [28], as seen in Fig.8.

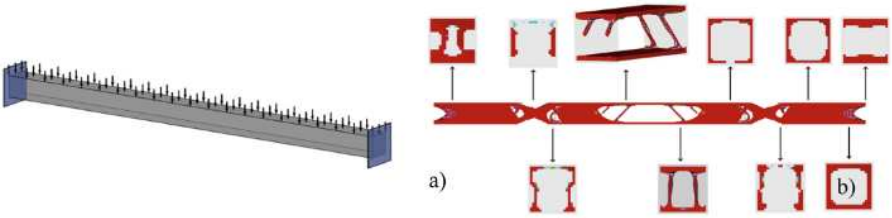
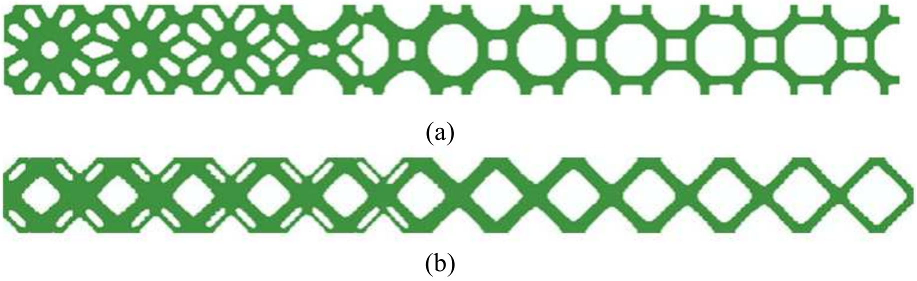


Fig.8. STO on a fixed-ended beam (a) Optimisation input (b) Variable cross sections in optimised beam [28].

3.2 Additively manufactured functionally graded materials

Functionally graded materials (FGM) are advanced materials characterised by the gradual change of properties within the material, which enables multi-functional performances within a part. Such materials are composed of a series of self-repeating base cells [29]. Mechanical properties of FGM vary according to the structure of unit cell and the direction in which the base units are assembled. Its application in engineering, especially in the construction sector, is still rare due to the limited knowledge as well as the difficulty and cost to manufacture using traditional processes. The excellent adaptability in properties of FGM offers potential advantages in structural engineering, especially for the structures subjected to complex loading conditions. Engineers can tailor the FGM based on the performance requirements. AM with high geometric freedom is well-suited to the production of such materials and this topic needs further exploration.

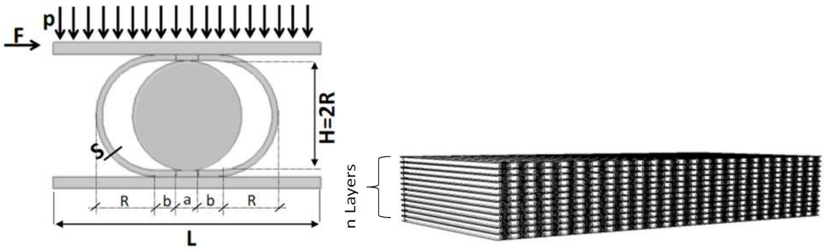
It has been indicated in a previous study that, just like macro-level structures, the unit cell of FGM can also be modified via STO to achieve better material properties with minimum weight [29]. As shown in Fig.9, cross-sections of the unit cells were designed to change gradually to achieve continuously varying moduli of elasticity and linearly varying shear moduli.


(a)

(b)

Fig.9. Optimised cross-section of FGM with (a) nonlinearly varying modulus of elasticity (b) linearly varying shear modulus of elasticity [29].

Lomiento and Valdevit [30] proposed an innovative seismic insulation device using functionally graded cellular materials which exhibited substantial improvements in flexibility. A special unit cell structure was used at the millimetre scale to tailor the mechanical properties of the device. The structure was composed of two plates, at the top and bottom, an internal core that is free to roll, and a cylindrical shell in the middle which connects them together (Fig.10). The design of the internal roll enables the structure with strong vertical stiffness but relatively lower lateral stiffness, which results in improved lateral flexibility. The unit cell was then assembled layer-by-layer to form the material of the isolator [30].



(a) (b)

Fig.10. Cellar periodic material for seismic insulator (a) Structure of unit cell (b) Assembly of unit cells in layers [30].

Unlike conventional cellular material which absorbs energy by plastic deformation, Izard et al. [31] introduced negative stiffness elements in the unit cell to dissipate energy in a recoverable way (see Fig.11). Similarity, Correa [32] proposed negative stiffness honeycombs with high initial stiffness and recoverable energy dissipation. This design (see Fig.12) achieved about 65% more energy absorption under displacement-driven cyclic loading compared with conventional hexagonal honeycombs.

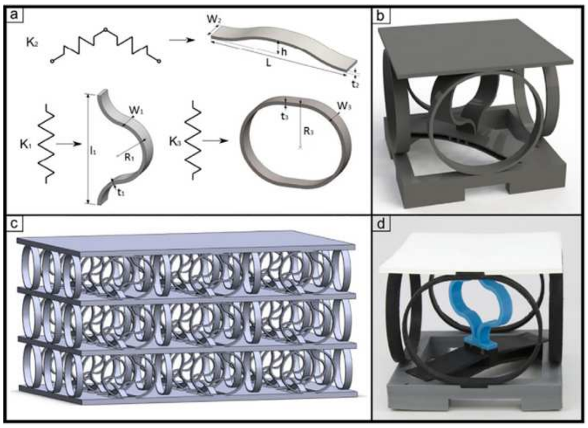
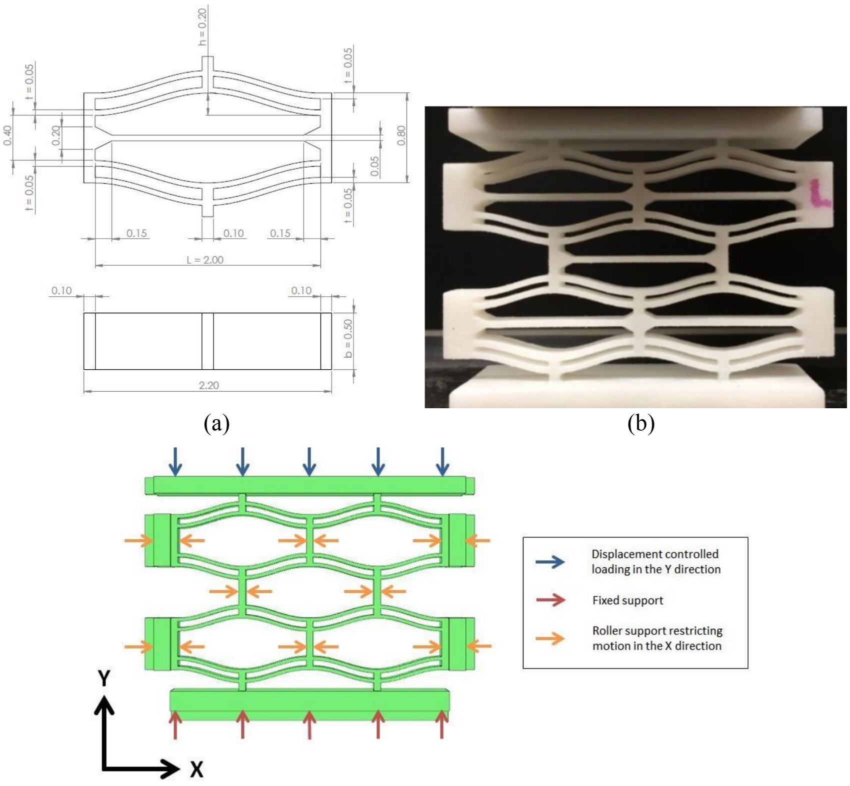


Fig.11. Unit cell with two positive stiffness elements and one negative stiffness element (a) configuration of unit cell (b) numerical model of unit cell (c) three-dimensional lattice material (d) 3D printed model of unit cell [31].

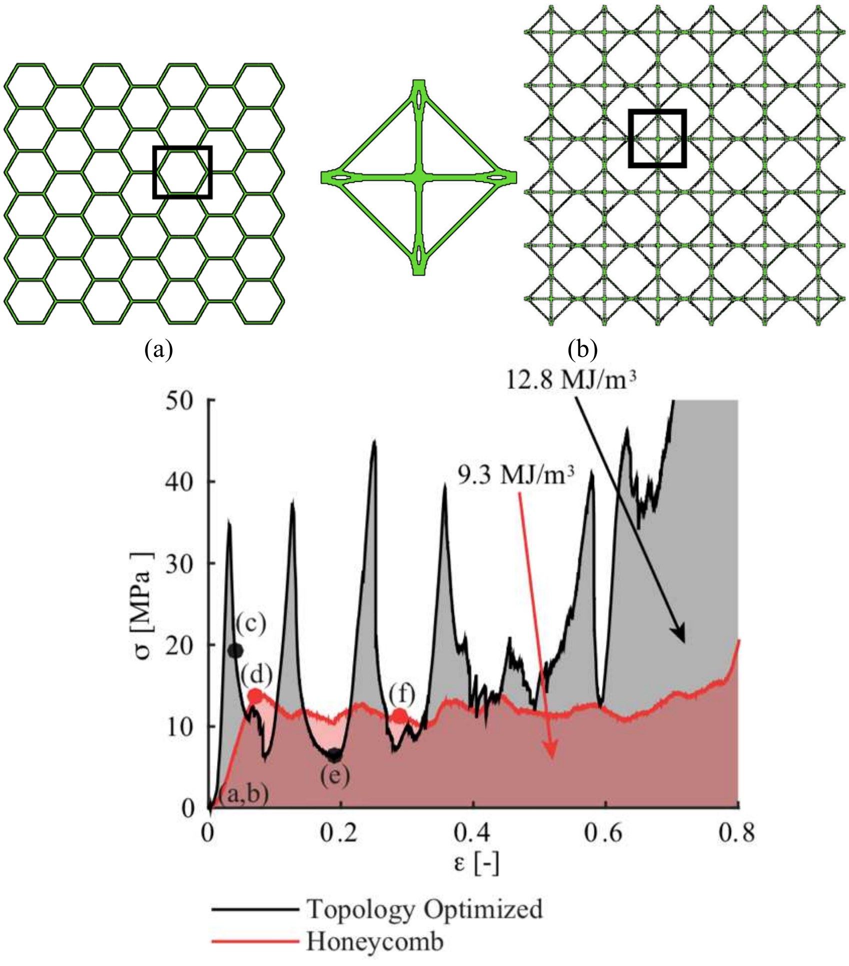


(a) (b)

(c)

Fig.12. Negative stiffness honeycombs (a) prototype of unit cell with rigid central beam providing horizontal reinforcement (b) 3D printed negative stiffness honeycombs (c) mechanism of negative stiffness honeycombs [32].

Carstensen et al. [33] proposed formulation for STO considering the material and geometric nonlinear elastic designs, which can maximise the energy absorbing capacity of cellular material. Compared with the conventional honeycomb structure, the optimised cellular structure generated from the formulation improved the energy absorption of brittle material bulk metallic glasses by 38%. This study shows tremendous opportunities of exploring new capacities of existing materials.



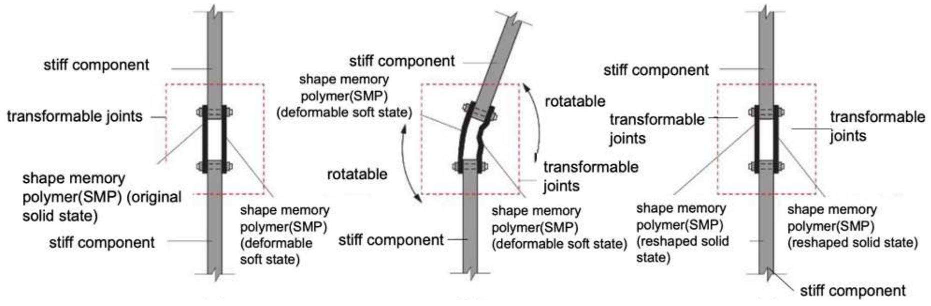
(c)

Fig.13 STO on bulk metallic glasses with nonlinear mechanics (a) honeycomb cellular structure (b) optimised cellular structure (c) experimental stress-strain response [33].

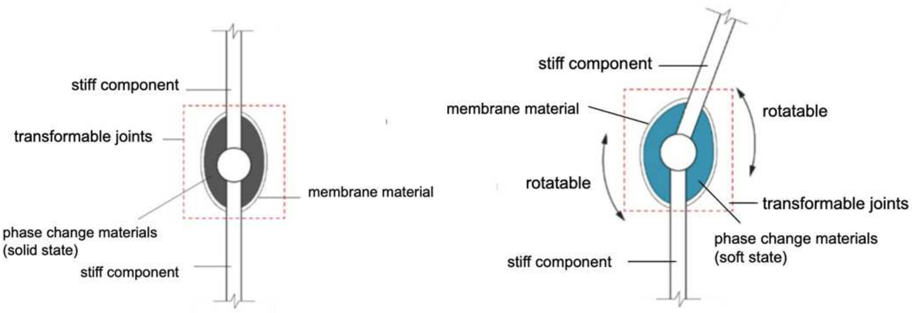
The FGM designs mentioned above all hold great potential for connection designs in modular building systems, especially for those designed for high-rise buildings since it is dominated by lateral resistance. FGM allows directional variety in connection property, and those with negative stiffness elements can increase the damping of the overall structure for achieving better seismic and wind performance. Apart from the weight reduction, the highly customised property of FGM provides the structural engineer with more freedom in connection design and the opportunity to solve more complicated structural problems.

3.3 Adaptive structures

Adaptive structure is another innovative method to improve material property that is characterised by the adaptive stiffness and adaptive geometry [34]; the stiffness adaption of which is normally achieved by connecting stiff components and flexible components via joints with transformation mechanisms as seen in Fig.14 [35]. The inherent properties of these structures can passively or actively adjust beneficially in response to external stimulations [36]. Active control systems have been shown to be effective in controlling the dynamic response of structures such as displacement and acceleration [37], [38], [39] and Fig.15. The concept of adaptive structures can also be the inspiration for 3D printed smart material, e.g., the joint between unit elements, to achieve positive adeptness in material properties. Smart materials such as shape memory polymers (SMPs) and phase change materials (PCMs) are normally used to form adaptive structures. The adaptive structure composed of SMPs can withstand significant stiffness reduction under excitation and recover afterwards (Fig.14a). PCM normally have two phases and its stiffness changes during the phase transition due to the change of temperature.



(a)



(b)

Fig.14. Examples of transformable joints (a) shape memory polymer (SMP) joints at original solid state (left), deformed soft state (middle) and recovered state (right) (b) phase change material (PCM) joints at solid state (left) and soft state (right) [35].

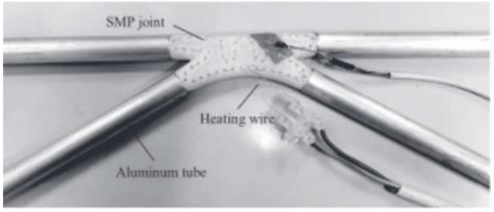


Fig.15. 3D printed shape memory joint with adaptive thermomechanical properties [39].

3.4 Challenges of applying addictively manufactured materials in connection design

Despite the benefits, constraints still exist in the practical application of the aforementioned materials and structures. FGM is still a new emerging technology so most of the analyses have been carried out numerically. Experimental evidence on the efficacy of FGM material is currently insufficient. Moreover, the mass production of FGM is still problematic. It has been demonstrated that FGM is highly sensitive to dimensional changes to the unit cell and the process parameter sets of AM, such as laser power, scan speed, layer thickness, and more [21], [25], [37]. Therefore, high accuracy is required in FGM manufacturing, so Selective Laser Melting (SLM) and Electron Beam Melting (EBM) could be better AM options [37]. Currently, no specification is available to assess these impacts during manufacture [25], [21]. So further studies are necessary to optimise the AM process for more accurate geometry and property control to achieve a stable outcome in material properties. Moreover, for the practical application, comprehensive databases for addictively manufactured FGM needs to be set up [40].

Another main restriction of the large-scale application of AM in the construction sector is the cost. AM is now mainly used in prototype production. With the constant improving technology and the elapse of patents, the market of the 3D printing will open up and the price will gradually reduce, making it more feasible for general manufacturing process. Frankly, AM is highly independent to the geometry so it can manufacture different products without requiring additional assembly line setup which is expensive and time-consuming [41]. It is therefore well justified to believe that with the development of AM, 3D printed functionally graded material can become reality in the near future, which means that highly efficient connection designs with customised geometries and tailored properties will be possible.

4 Conclusions

To further improve the eco-friendliness and efficiency of modular construction and in particular modular building systems, the flexibility as well as the demountability of modular components and thus their connection systems need to be re-considered. The concept of interlocking system has been adopted in some innovative connection designs to reduce the use of additional connectors, while they are still constrained by the limitation of conventional manufacturing methods, cost, and understanding performance. additive manufacturing (AM) is a rapidly developing technology which can bring new possibilities to complex connection design. The geometric freedom offered by AM together with innovative materials can be achieved with the use of powerful optimisation tools fostering the development of resilient and adaptable prototype connection designs. This paper provides ideas and thoughts of how interlocking connections, structural topology optimisation (STO), and functionally graded materials (FGM) can be all integrated to improve the adaptability of modular building connections via exploiting AM potentials according to existing studies. Future work involves the geometric design of interlocking systems as well as unit cells of FGM that are suitable for modular joints and connections with specifically optimised mechanical performance.

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