Slide-By-Slide: Design for Disassembly through Geometric Innovation of Reversible Joints

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Abstract

This paper describes the discovery, development, and geometric configuration of a novel structural system in an interplay of seemingly conflicting forces. While some geometric configurations result in an aesthetically pleasing form, have a structurally robust outcome, enjoy easy assembly, or easily permit standardised components, a structural system that embodies all these factors simultaneously is rare. Our design system, which we call "*vve construct*," developed through nine years of teaching and research-based design development at the Chinese University of Hong Kong, highlights a unique configuration: a structurally robust form that enables contemporary design values such as circularity, adaptability, and design for disassembly at the scale of furniture and single-story installations.

Issue: Reversible Joints, Integral Mechanical Attachment and Their Misadventures

In panel structures, the design of joints is critical, particularly when systems are intended for several rounds of assembly, disassembly, and reassembly. Unlike conventional timber structures that rely on pins and adhesives, our system employs what is called "Integral Mechanical Attachment," where mechanical connections are derived from the geometry of the components themselves [4]. Traditional carpentry techniques, such as mortise-and-tenons, lap joints, and dovetail joints, exemplify this type of joint. Traditional log construction systems are also an example of a system that enables the assembly of components without mechanical fasteners.

Figure 1: *Integral Mechanical Attachment of the traditional Log Construction System*

The key advantage of Integral Mechanical Attachments relative to other conventional methods is the possibility of disassembly and reassembly of the structure in other locations and on other occasions. However, Design for Disassembly (DfD) in timber and panel structures faces feasibility challenges, particularly in today's environment, where cost, time, and budget are the key forces of production. For instance, carpentry joints are theoretically reversible, but their stiffness and strength often do not meet the requirements of modern timber structures [5]. As the demand for mass production grew, traditional Integral Mechanical Attachments mainly were replaced by mass-produced fasteners, including screws and dowels, as well as advanced adhesive techniques [6].

In recent years, the issue of low recycling rates in the construction industry has reignited interest in DfD among designers in both academia and practice. Some argue that the challenge of DfD in contemporary practice can be successfully addressed with the emergence of advanced digital geometry processing tools and technologies. While the complexity of traditional connections posed challenges for manual production, these techniques can be handled with algorithmic processing and digital fabrication. The design-research projects of Christopher Robeller and Yves Weinand showcase an attempt at Integral Mechanical Attachment through digital and robotic tools [7].

Despite some successful exemplars of digital and robotic tools, the widespread accessibility and economical application of such methods still remains a challenge. But perhaps, in this age and context, a more fundamental question can be asked: Is the pursuit of DfD through Integral Mechanical Attachment purely a technological problem? If not, can reversible joints be reimagined and redesigned through a nuanced consideration of geometric complexity, structural performance, construction logic, and cost? The following section presents a novel design system, the ”vve construct,” that enables such a balanced approach, not through a merely technological take but instead a unique geometric configuration.

Innovation: A Structure with Four Identical Components

The basic unit of the invention is a structure formed by the intersections of four planes. The first form that this unit took was discovered through a series of teaching exercises of a building technology course at our university in Hong Kong. In this process, together with students, we started prototyping with perpendicular cutting slots, which is a more common practice for this type of structure. After several rounds of trial and failure, we adopted a diagonal cutting slot, which would allow the upper and/or lower components to connect and thus make the unit structurally stronger.

So far, we have discovered four basic units from this logic of diagonal cutting slots: 1) the upper two panels connected at the top (appearing as a lambda Λ) stacked on the lower two panels connected at their top (appearing as a Λ); 2) two upper panels connected at the bottom (appearing as a V) stacked on the lower two panels connected at the bottom (appearing as a V); 3) two upper panels connected at the top (appearing as a Λ) stacked on two lower panels connected at the bottom (appearing as a V); and 4) two upper panels connected at the bottom (appearing as a V) stacked on the lower two panels connected at the top (appearing as a Λ).

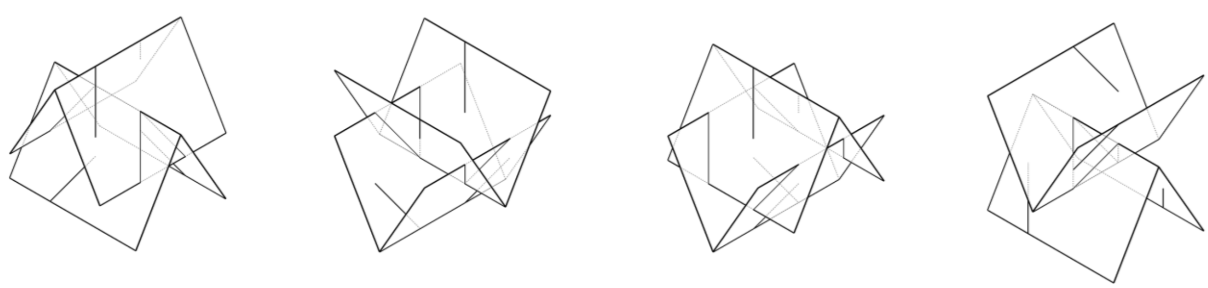

Figure 2: *Four different basic unit types in which all four components are identical.*

It is worth noting that the additional cut on the upper and lower panels in Figure 3. is to enable the stacking of the same units from the top and the bottom. We also note that the first two types of units in Figure 2. are identical to each other up to an upside-down flip. Nevertheless, since the paths of forces and structural performance of these types are different, we categorise them separately. In any configuration, if the angle between the upper and lower two panels is identical, then all four components can be identical if the insertion cutting slots are located in the correct location on the panel. If the angle between the upper and lower panels is different, the insertion cutting slots of the two panels can be identical except for the angle of the slot within the panel. The following describes the geometric relationship between the four panels and the angle of the insertion cutting slots.

We consider the configuration of panels as in Figure 3. Our coordinate system in three dimensions is such that the line of intersection between the lower two panels is the y-axis and the two panels meet at an angle α. The upper two panels are a vertically shifted 90-degree rotation of the lower two panels. For greater generality, we also permit these panels to meet at a distinct angle β. We use h to denote the total height of the structure, measured from the plane $z = 0$, where the lower two planes intersect to the plane $z = h$, where the two upper planes intersect. Angles γ and λ are the cut angles in the lower and upper planes, respectively. We show that all cut angles are independent of h and that:

$$\gamma = \cos^{-1}\left(\tan\left(\frac{\beta}{2}\right) \Big/ \sqrt{\tan^2\left(\frac{\alpha}{2}\right) + \tan^2\left(\frac{\beta}{2}\right) + 1} \right)$$

By symmetry, the cut angle λ in the top planks is given by the same formula, but with the variables α and β swapped. Of course, when the angles α and β are the same, all cutting slots in all panels are identical. To derive this formula, we first write down the equation that defines the bottom left plane. The plane contains the point $(0, 0, 0)$ and has a normal vector given by $((1, 0, \tan\left(\frac{\alpha}{2}\right))$. This is sufficient information to write down the formula for the plane as $\mathrm{x} + \mathrm{z}\tan\left(\frac{\alpha}{2}\right) = 0$. Turning to the left-hand side upper plane, we have by assumption that the point $(0, 0, h)$ lies on it and the normal vector of the plane is $(0, -1, \tan(\frac{\beta}{2}))$, yielding the plane equation $-y + (\mathrm{z} - \mathrm{h})\tan\left(\frac{\beta}{2}\right) = 0$. The cut angle in the bottom plane lies along the line L of the intersection of these two planes, which is parametrised by:

$$L = \left\{ \left(-z\tan\left(\frac{\alpha}{2}\right), (z - h)\tan\left(\frac{\beta}{2}\right), z\right) \right\}_{z\in\mathbb{R}}$$

The angle γ that L makes on the lower plank is the same as the angle at which L intersects the y-axis. To compute γ, it suffices to compute the angle between the y-axis unit vector $u = (0,1,0)$ and v where v is a vector pointing between two points on L. To find a suitable v, we evaluate the parametrisation of L at $z = 0$ and $z = 1$ and take the difference vector, obtaining $v = (-\tan\left(\frac{\alpha}{2}\right), \tan\left(\frac{\beta}{2}\right), 1)$. The angle between u and v is then

$$\cos^{-1}\left(u \cdot v \big/ |u| \cdot |v| \right) = \cos^{-1}\left(\tan\left(\frac{\beta}{2}\right) \Big/ |v| \right)$$

The formula is then derived by taking the norm of v.

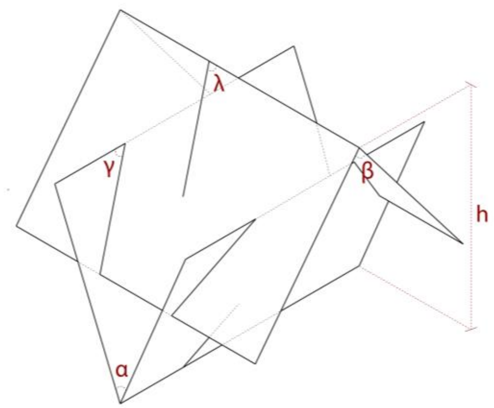

Figure 3: *Geometric relationship between the four panels.*

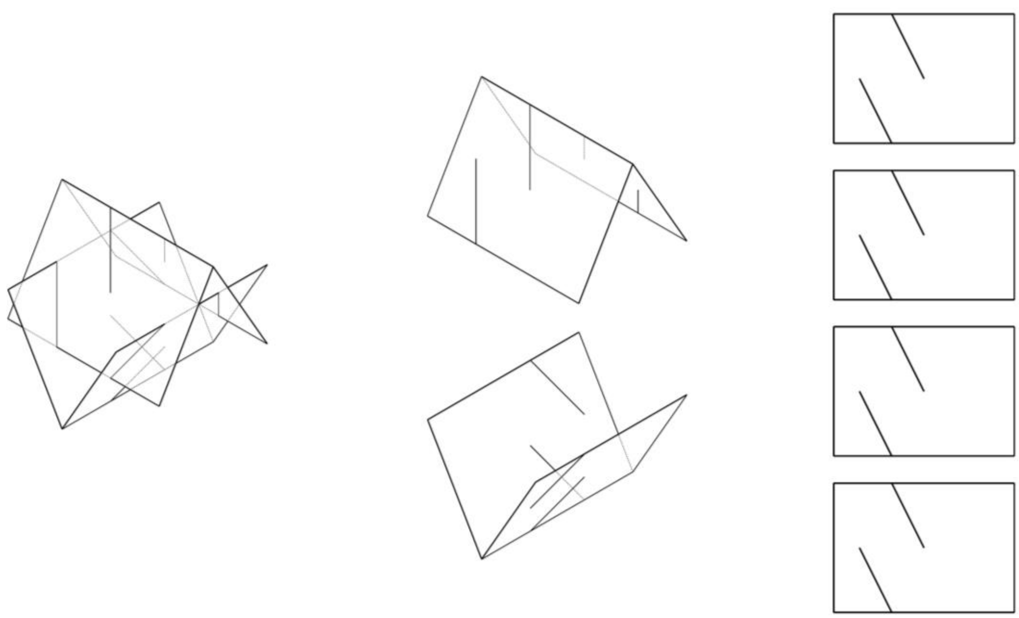

Figure 4: *Assembly logic of the four identical components of the invented structure.*

Comparison to Prior Works with Similar Structures

While similar geometric configurations exist—such as those proposed by George Hart and Rinus Roelofs—this system distinguishes itself through its unique cutting slot configuration and assembly process. Hart presented a similar structure in 2004 at the Bridges Conference titled "Slide-Together" [3]. His proposal utilises identical elements with identical cutting slots based on geometries, such as hexagons, decagrams, and pentagrams, that slide together to form a structurally stable whole. In his proposal, however, the elements have to be made out of paper or other bendable materials since some have to bend during the assembly process. Two years later, at the Bridges Conference, Roelofs proposed an alternative design that would allow a similar structural whole but using rigid components. His innovation is to use "halfway cuts," which allow the assembly of rigid components to arrive at different forms, particularly tetrahedral structures [8]. Nevertheless, the halfway cuts require a unique type of assembly operation in which all components have to be inserted simultaneously; otherwise, the structure cannot be assembled.

Figure 5: *Teaching-based exercise for reversible connections using diagonal cutting slots.*

This paper proposes a unique configuration and cutting slot arrangement that allows for the sequential assembly of rigid identical parts. Unlike Hart's design, which relies on bendable components, or Roelofs's proposal, which requires a simultaneous assembly process, our system supports one-at-a-time assembly of identical components—slide by slide. This brings about significant assembly efficiency as well as structural advantages. It should also be mentioned that our system was not designed with the initial intent of improving existing systems. It was rather an accidental discovery through a series of teaching-based exercises at a university designed to explore the hidden potentials of reversible connections of traditional log systems [9]. Furthermore, geometric configurations are only the starting points of a design system, and other building considerations should be incorporated as well. In our case, numerous issues, such as material, joint details, and tolerances, among many others, were addressed incrementally through a series of prototypes.

Titled "*vve construct*," this system is characterised by two primary features: first, its unique yet simple joint design that allows for the easy assembly and disassembly of lightweight panels by sliding them in and out of the cutting slots on the lower panels. Second, after the assembly of four panels, a strong and distinctive geometric configuration is formed, resembling a V and a Λ. Because of these two features, the panels press against each other when vertical forces are applied. This provides the system with a notable economic, structural, and operational edge when designing and building furniture and temporary installations. Because of these features, any furniture made of this system can be easily assembled and disassembled by non-specialist individuals. The combination of the word "we", representing the collective agency associated with the assembly of this system and its appearance involving multiple planes in the shape of Vs provided us the name *vve construct*. In what follows, we provide two functional prototypes formed by the repeated composition of our basic unit. Other than these two prototypes, there are also other installations generated from this system, such as vertical farming pavilions, dining tables, and benches. [1]

Prototype: Two-Sided Bench

This is the first 1/1 scale prototype of this system, designed and built in December 2018. At that time, we had only designed and built a boundary wall as part of a teaching exercise in our university, as illustrated in Fig. 5. As a result, the load-bearing performance of the system was not tested. This led us to an important open question: whether these interlocking spatial panels were strong enough to carry human weight. The logical start was to work with the basic units. After some trials and failures in a 1/5 scale model, it quickly became evident that some adjustments were needed to withstand lateral forces. To do so, we merged two of the basic units and tilted some of the components for further stability. Although this operation challenged the standardisation of components and increased the number of types, it greatly helped with the structural performance. Also, while designing this bench, other considerations were considered, such as combinations with other identical benches and also dual functionality, enabling it to be flipped over to serve as a desk.

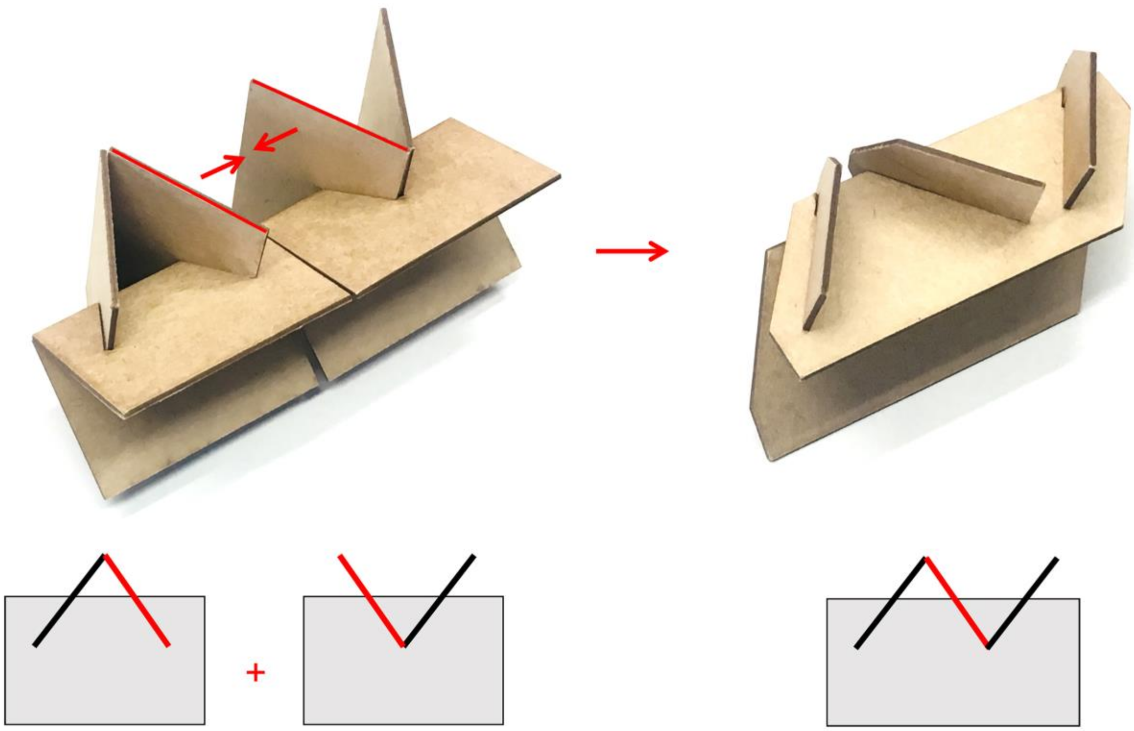

Figure 6: *Design of the Two-Sided Bench from the invented unit.*

Figure 7: *Two-sided bench and its various uses*

Prototype: Half Pavilion

Designed for the "Tianfu Construction Festival" in 2023, this pavilion was created under the constraints of an extremely low budget and a tight three-day construction timeline. The pavilion was to be disassembled one month after its construction. Given these conditions, the system proved to be a suitable choice, allowing for the production and assembly of lightweight plywood panels in less than one day. Indeed, our undergraduate students did the entire manufacturing and assembly process without needing any heavy or sophisticated machinery. [2].

Figure 8: *Assembly process of the Half Pavilion.*

Figure 9: *Half Pavilion.*

Summary and Conclusion

This teaching-based design project is a demonstration of how traditional building methods can inspire novel geometric configurations and design systems that meet contemporary needs. Through a series of design-based exercises at university, we explored the unrealised potential of the wooden construction systems that need no mechanical fasteners, which led to developing a unique structural unit. The impact of this structural system lies in its potential to influence DfD practices, particularly regarding reversible connections and Integral Mechanical Attachment. By addressing the limitations of traditional carpentry joints and log construction system, the proposed structure enables assembly, disassembly, and reassembly of identical rigid components at the scale of furniture and single-storey installations. This highlights that a novel design system should not be approached merely from geometric innovation or assembly or structure but rather a fine balance between varied and seemingly contradictory forces.

Acknowledgements

This teaching-based project began in 2016 in a course titled "Building Technology I: Materials and Construction" at the School of Architecture at the Chinese University of Hong Kong, coordinated by Prof. Zhu Jingxiang and co-instructed by the first author. Over two years of exploration with students, the first author discovered this unique geometric configuration and joint design, further developing the system through a series of prototypes. The title “*vve construct*” is used to describe this system in various contexts. We would like to acknowledge Dr Han Man for his contribution to the design and also the BSSc Year 2 students, Chung Hiu Nam, Mak Kwan Yeung, Wang Yilan for their contribution to the assembly of the *Half Pavilion*.

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