

Experimental assessment of Kagome weaving for architectural structures using physical models

Xan BROWNE*, Shayla NIKZAD, Ji YOU-WEN, Oliwia PINDEL, Jack YOUNG, Phil AYRES

*Royal Danish Academy – Architecture, Design, Conservation
Philip de langes alle, 10, 1435, Copenhagen, Denmark
xbro@kglakademi.dk

Abstract

Woven Kagome lattices present a promising architectural structural typology capable of generating doubly curved geometries from straight stock materials through topological organisation and material interlacing. While previous studies have explored Kagome gridshells through computational analysis and fixed-joint experimental systems, there remains little understanding of the structural behaviour of interlaced Kagome lattices under architectural loading conditions. This paper investigates how member bending stiffness and connection type influence the global displacement behaviour of woven Kagome lattices through two physical model experiments. Twenty-one small-scale specimens of identical topology and positive Gaussian curvature were fabricated using two polyethylene materials with varying cross-sections and subjected to incremental uniformly distributed loading. A subsequent experiment compared the performance of interlaced and pinned connections under asymmetric point loading. Results reveal multiple displacement and buckling modes, strong sensitivity to member bending stiffness, and significant differences between connection types, with pinned and interlaced joints exhibiting approximately three times greater stiffness than joints only interlaced. The findings suggest that the structural response of woven Kagome systems depends substantially on member bending behaviour and connection slip, providing experimental insight for dimensional analysis, numerical model calibration, and the development of architectural shell structures based on interlaced lattices.

Keywords: gridshells, kagome, lattice structures, experimental testing, physical models, structural analysis

1. Introduction

The potential of woven Kagome lattices as a typology for architectural structures is evolving through recent built works that demonstrate Kagome’s capacity to utilise readily available materials for diverse morphologies, exemplifying a variety of spatial qualities and loading conditions [1]. These examples reflect the historic affordances of Kagome’s craft origins in basketry, that utilise a variety of straight stock formats to generate complex curvatures, achieved through specific topological relations [2].

The interest in Kagome lattices for architectural scale application has motivated studies into its structural performance. Recent experimental work has investigated the structural performance of Kagome patterns. These have looked at multi-layered buildups with additional screwed in shear blocks [3], spherical geometries using a combination of continuous and half-continuous layers [4], and hyperbolic geometries with fixed nodes from curved strips [5]. Another study, that used interlacing instead of fastenings, made a coarse photographic comparison of the deformation between a 1:9 model and a full-

scale structure, in which the latter is more greatly affected by self-weight [6]. Further work that has investigated theoretical comparisons of grid-shell typologies has revealed that Kagome patterns pose structural advantages over their quadrangular counterparts, owing to higher in-plane shear stiffness when comparing buckling modes [7].

While these efforts offer significant insight into Kagome as a structural system, there remains a lack of experimental study into how interlaced Kagome structures perform under architectural loads. In this paper, we ask how member bending stiffness and connection type influence the global displacement behaviour of woven Kagome lattices under distributed and asymmetric loading. This is investigated through the experimental validation of samples under uniformly distributed loads (UDL) with a focus on the displacement behaviour of different cross-sections. Secondly, we experimentally validate the relative performance of interlaced, and pinned and interlaced intersections through incremental asymmetric point loads.

2. Materials and methods

2.1 Physical models for structural analysis

Particularly prior to advances in computation, physical models were widely applied to gain understanding of structural phenomena [8]. Inverse funiculars are a well-known example of a scale-independent model that have been popularised through the theory of Hooke and the built works of Gaudi among many others [9]. Scale-dependent models, however, expanded the quantitative application of physical models for structural analysis after the development of necessary mathematical theory to account for the non-linearity of scaling laws [10]. Famous examples include the concepts developed by Reynolds, Froude, and Buckingham in which dimensionless quantities could be derived to empirically assess phenomena using smaller scales and different materials.

In this study, we are inspired by the methods used for the structural validation of early ambitious grid-shell structures, such as Multihalle Mannheim. The insight gained through a sequence of tests of physical models and large-scale prototypes led to sufficient confidence for realising the full-scale structure [11], [12]. As a methodological framework, it is also an enticing precedent for how to empirically advance understanding of a novel structural system prior to establishing numerical models, as well as showcasing the possibilities of physical models to predict the behaviours of large-scale structures.

Due to the complex nature of grid-shells, there remain strong arguments for using physical models to understand their behaviour. Alternatives, such as shell theory, are obscure and overly optimistic, where computational numerical analysis can produce significant inaccuracies, especially in preliminary studies [13]. As an alternative, physical models are useful for gaining both qualitative insight, predictions of behaviours at larger scales through dimensional analysis, and calibration of numerical models.

In this study, we have selected physical model testing as an expedient means to test a novel structural typology with a reasonable level of statistical sufficiency. This is further motivated by the absence of validated numerical models for Kagome lattices, highlighting the necessity of empirical experiments to obtain a dataset for numerical model calibration and a foundation for dimensional analysis.

2.2. Samples

The shape of woven Kagome lattices are defined by their topology, where synclastic or anticlastic curvatures are induced by the strategic placement of lower sided or higher sided singularities respectively [14]. In this study, we opt for a dome like geometry, achieved by a pentagonal singularity in the centre, resulting in global 5-fold symmetry (Figure 1). This serves as a foundational shape, with consistency in boundary conditions and loading points on each of the 5 sides. The effect of a UDL is

approximated by defining 30 loading points across the samples that are distributed as evenly as practical, all located above intersection points on the upper member.

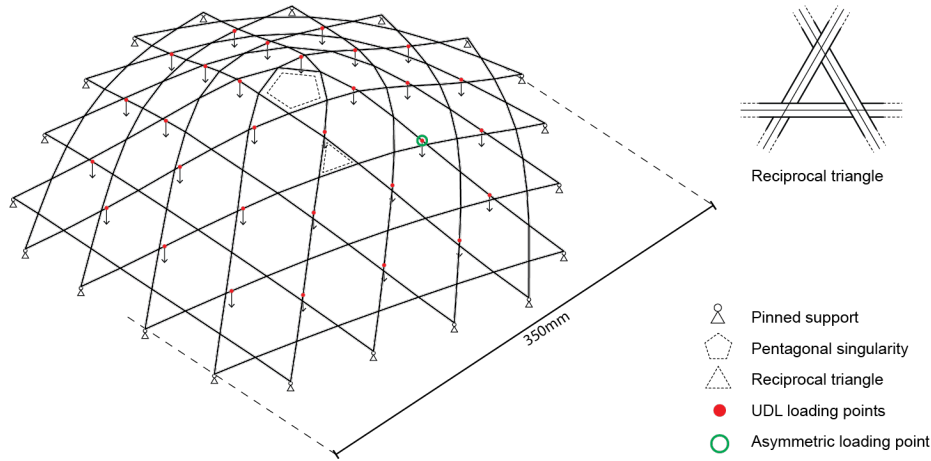


Figure 1. Base topology for all samples including the locations of UDL and asymmetric loading points, pinned supports, and singularity.

2.2.1. Materials

Kagome weaving is possible using a variety of materials, where many examples exploit the properties of pliable fibrous materials such as rattan and bamboo. In this study, pre-tests using rattan revealed that material heterogeneity, and cross-section inconsistencies have a significant impact on displacement behaviour when loading at this small scale. Therefore, alternative weaving materials were identified. Polyethylene terephthalate glycol (PETG), commercially available as Vivak, and high-density polyethylene (HDPE) were used for their consistency and the ease of cutting into specific dimensions. The Young's modulus of the two materials is 2.1GPa for the PETG, and 1.0GPa for the HDPE.

Table 1 describes each of the sample variants where span, topology, and the edge lengths of reciprocal triangles are constant, the only variables being material type, cross-section, and intersection type. Three replicates were fabricated for conditions 1 to 7. The samples from conditions 1 and 3 were further used for the asymmetric loading as conditions 1.1, 1.2, 3.1, and 3.2, where intersection types are compared.

Condition	Material	Cross-section (mm)	Intersection
1	PETG	4.0x1.0	Interlaced
2	PETG	6.0x1.0	Interlaced
3	PETG	8.0x1.0	Interlaced
4	PETG	4.0x1.5	Interlaced
5	PETG	6.0x1.5	Interlaced
6	PETG	8.0x1.5	Interlaced
7	HDPE	4.0x1.0	Interlaced
1.1	PETG	4.0x1.0	Interlaced
1.2	PETG	4.0x1.0	Pinned and interlaced
3.1	PETG	8.0x1.0	Interlaced
3.2	PETG	8.0x1.0	Pinned and interlaced

Table 1. All conditions used in the study. Note that condition 7 is a different material.

2.2.2. Sample fabrication and treatment

Weaving strips were cut from sheet stock using a metal shear cutter. Since the shape making principles of Kagome weaving are topology driven, it can be challenging to make uniform replicates without a reference. 3D printed jigs, corresponding to each of the three cross-section widths, ensured that samples were fabricated with consistent reciprocal edge lengths and were uniform in scale (Figure 2). The jigs also guaranteed that the interlacing chirality (orientation of the weave) was consistent ensuring that all samples were assembled into the same configuration. 30 loading points were created by melting a 0.5mm hole for a corresponding 0.5mm copper wire. Lastly, the samples were placed in an oven at 65° to remove the elastic strain energy induced by the interlacing process, 10 minutes for PETG and 20 minutes for HDPE. This final thermal relaxation step is used to approximate a technique for making Kagome structures from hardwoods in which timber is plastically formed into sinusoidal woven interlaces.

2.3. Test set-up, loading procedure and measurement

A loading rig was fabricated from MDF (medium density fibreboard) with a pentagonal shape corresponding to the naked edge of the woven samples. These edges are clamped by bolts and washers, that are connected to soft rubber balls seated in low friction adjustable attachments to the MDF rig. This allows the support points to rotate freely as a pin joint. A set of weight denominations from 10g to 200g enabled many different loading configurations to be defined.

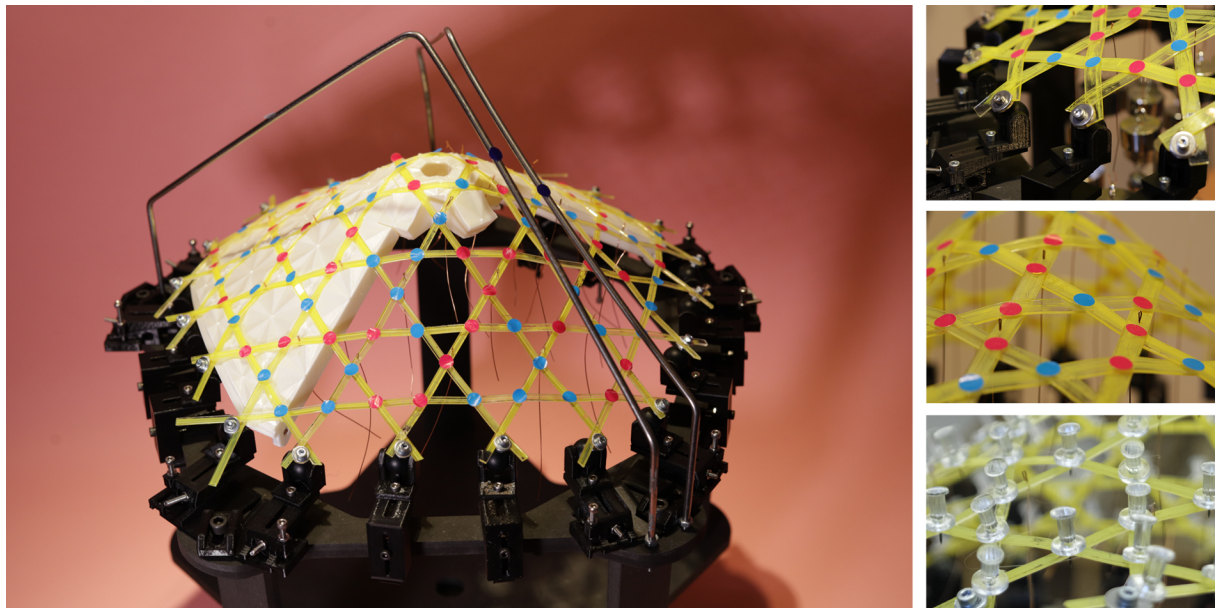


Figure 2. MDF loading rig with sample, two faces of the 3D printed fabrication jig are removed (left), close-up of pin supports (top right), close-up of interlacing and loading wires (middle right), close-up of pinned and interlaced connections (bottom right).

2.3.1. Experiment 1: Incremental uniformly distributed load and displacement

Experiment 1 subjected all samples to incremental UDLs with global displacement registered at each loading increment. This aimed to establish an understanding of the relationship between material cross-section and displacement behaviour. The UDL increments were 300g, (600g for condition 7), 1500g,

1800g, 3000g followed by incremental unloading. In the instance where a sample inverted, the inversion load increment was recorded.

The global displacement registration required a digital pipeline. The samples were prepared with coloured dots along the centre lines of the weaving strips. Further coloured dots were fixed to the jig as a datum reference. The dots were registered at each loading increment using a Revopoint Metro X desktop 3D scanner, requiring samples to be rotated 360° on a dedicated turntable. Pointclouds of each loading increment were processed to identify the centre point of the coloured dots; dots were rejected from the dataset if an insufficient number of points had been registered.

The extrapolated points were then oriented for each series of loading increments enabling the lattice topology to be approximated. Comparing point locations for each loading increment enables displacement magnitudes and trajectories to be defined.

2.3.2. Experiment 2: Uniformly distributed load and asymmetrical point load

Experiment 2 subjected 6 samples of two different cross-sections to a continuous UDL and an incremental asymmetric point load. The samples from conditions 1 and 3 were used for conditions 1.1, 1.2, 3.1 and 3.2 as described in table 1, above. Two joint types were tested, interlaced and interlaced with pinning, with the aim of establishing the relative contribution of the two joint types on deflection. The pinned joints were made using 0.7mm pushpins by melting a corresponding hole at each intersection. Theoretically, these would transform the weave into a fully triangulated structure if the pins are entirely effective at transferring the shear forces. Asymmetrical point loading enables deflection registration to be simplified and mitigates the variety of buckling modes that occur when subjecting symmetrical shell structures to UDLs. This was decided after carrying out experiment 1, which showed significant variation in buckling behaviour across conditions and replicates.

The samples were loaded at increments of 50g as much as practically possible or until inversion. Deflection readings were taken using a ruler at the loading point after each loading increment. The constant UDL was 900g for conditions 1.1 and 1.2 and 1500g for conditions 3.1 and 3.2, distributed across 30 points. The difference in the two UDL constants is to account for the divergence in capacity of the two conditions, based on the findings from experiment 1.

3. Results

3.1. Experiment 1: UDL and displacement

Figure 3 describes the relative displacement of all samples showing a significant range of displacement behaviours and values across conditions and replicates. As would be expected, variants with a higher Young's modulus or larger cross-section have a greater resistance to displacement. Some conditions inverted prior to completing all loading increments. Condition 1 inverted at 1500g with the exception of replicate 1, and condition 2 inverted at 1800g.

The variety of displacement behaviours is typical of symmetrical shell buckling under universal loading, that is highly sensitive to fabrication imperfection, loading inconsistency, and unknown externalities that occur during testing [15]. However, the results do show a coarse trend across samples and can be categorised into the following displacement modes: uniform displacement (e.g. 4.0x1.5-2), single face displacement (e.g. 8.0x1.0-3), and two face displacement (e.g. 4.0x1.0-2).

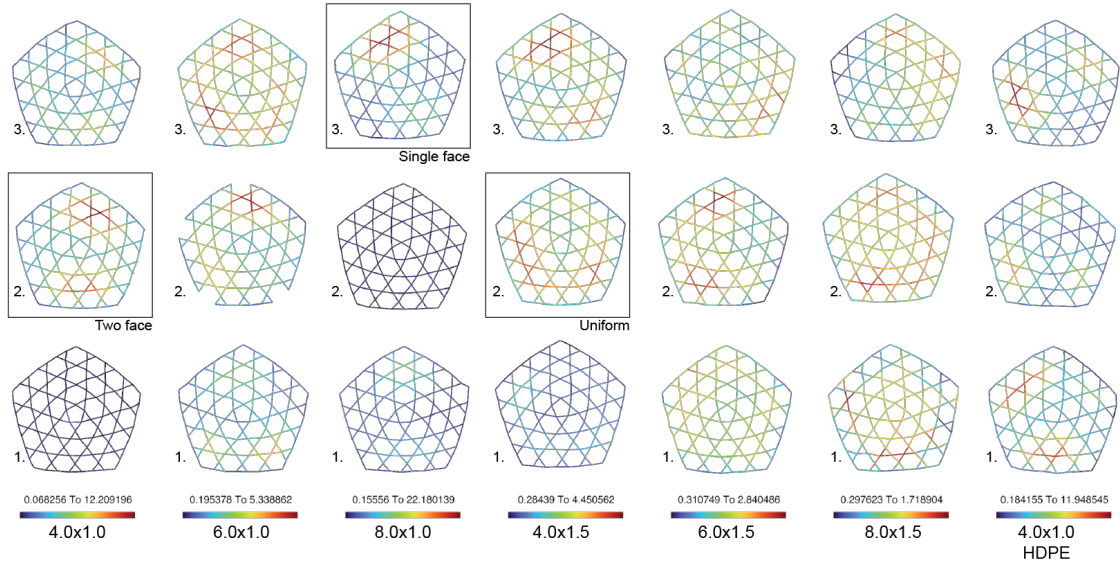


Figure 3: Relative displacement of all three replicates for each condition. Examples of the three displacement categories are highlighted: two face, single face, and uniform.

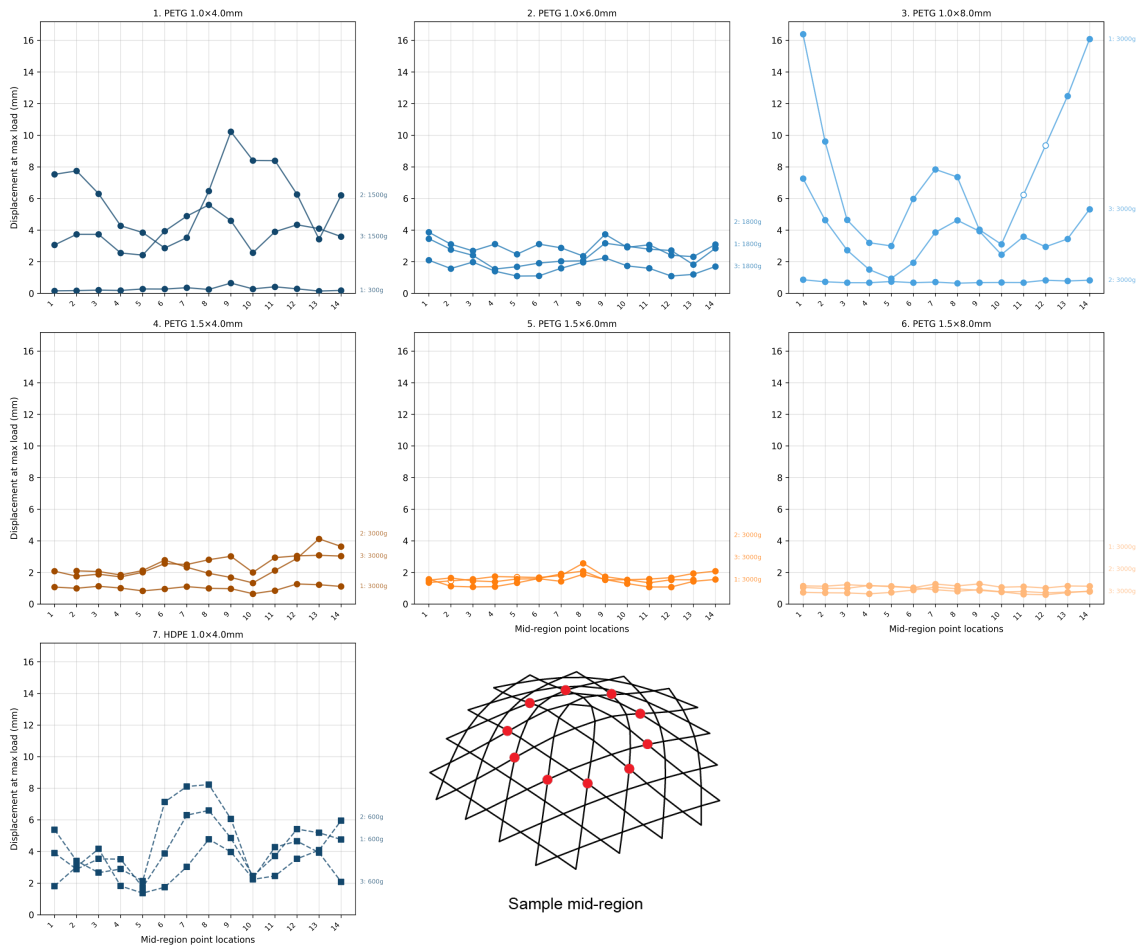


Figure 4: Displacement values at the mid-region of all samples for each condition, hollow dots are interpolated due to missing scan data.

The displacement modes are further described in figure 4. Each graph plots the displacement values for all three replicates at the mid-region of the sample. This is the area with the highest displacement as well as exhibiting the most variation.

Figure 5 shows the displacement of the pentagonal singularity for all samples at each loading increment. Although this is not the region of highest displacement, it is the region with the most consistent displacement in the dataset. The range of cross-sections across conditions offers insight into the relative contribution of the width and depth of the members. Conditions 2 (6x1mm) and 4 (4x1.5mm) have the same member cross section area, however Condition 4 is shown to be approximately twice as stiff as Condition 2, suggesting that member depth makes a larger contribution to global stiffness.

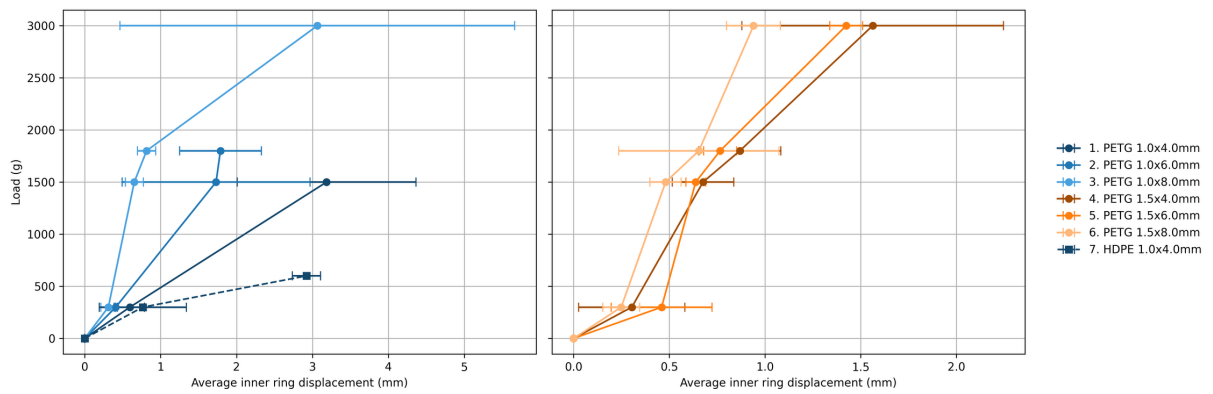


Figure 5: Displacement of the pentagonal singularity of all samples at each UDL increment.

3.2. Experiment 2: Constant UDL and asymmetric point loading

Experiment 2 further tested conditions 1 and 3 with a constant UDL and an incremental point load. The difference in testing procedure to experiment 1 simplified both loading and measurement as well as deriving more consistent results. The experiment revealed a clear distinction between pinned and interlaced connections. Figure 6 shows that pinned joints are approximately three times stiffer than interlaced and that both intersection types show a decrease in stiffness as loading progresses. This non-linear behaviour is more prominent for the interlaced connections, which could be a result of slipping.

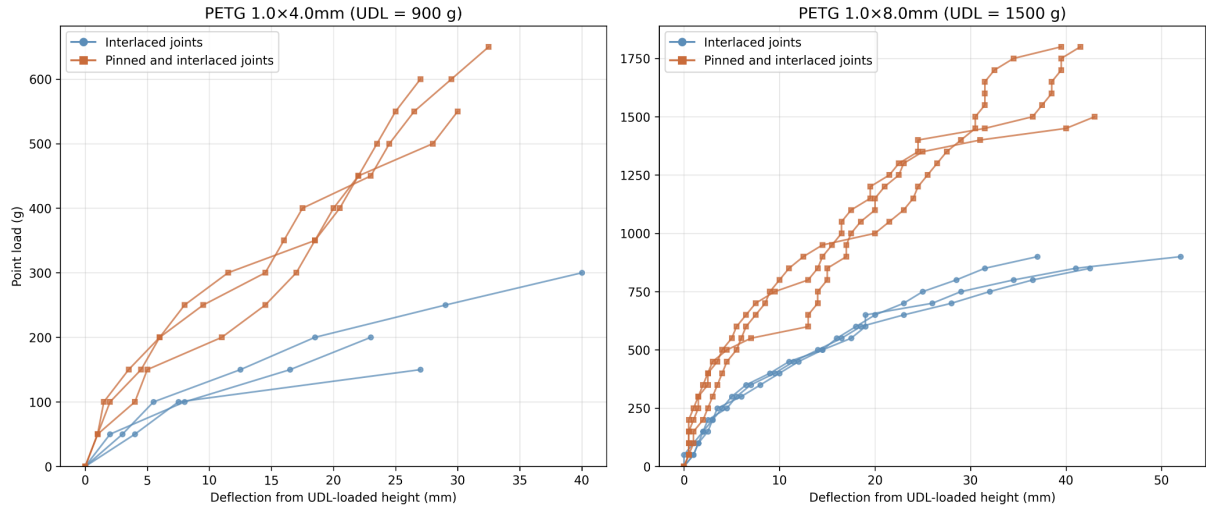


Figure 6. Asymmetrical point loading and deflection of conditions 1 and 3 with constant UDLs comparing interlaced and pinned joints. The values in the two graphs cannot be related directly since the constant UDL for the two conditions is different.

4. Discussion

4.1. Experiment summary and discussion

The two experiments offer new insight as an initial study into the behaviour of interlaced Kagome lattices as a structural system. This ranges from the general affordances of using small scale models for developing an empirical understanding of structural behaviour to a valuable dataset for calibrating numerical models, steering further experimental investigations, and predicting the behaviour of larger scale structures.

The first experiment, that subjected Kagome lattices to incremental UDLs revealed the variety of displacement types and some relationship between material properties, cross-sections, displacement, and inversion loads. These show that for a given topology, a UDL will lead to a variety of displacement modes, which also makes it challenging to derive conclusive relationships between the 7 conditions and displacement behaviour.

The second experiment, that subjected Kagome lattices to constant UDLs and incremental asymmetric point loads revealed the relative performance of interlaced and pinned connections, showing that pinned connections are approximately three times stiffer than interlaced. Further investigation will verify whether this relationship is reflected at larger scales and with other materials. For instance, scaling up and using an orthotropic material such as wood may exhibit different behaviours to the isotropic materials used here. Future application of Kagome lattices would benefit from identifying which material properties and weave features relate to the stiffness of the interlacing. Further parameters of study include the effects of friction coefficients and bending stiffness, as well as to what extent the sinusoidal undulation of weaving members influences their axial stiffness. Obtaining an understanding of what effects structural stiffness will allow lattice properties to be tailored for a given application. Low stiffness is not disadvantageous for applications such as spatial division, and can be an advantage, such as for transportation.

4.2. Membrane and bending theory

A key concept in shell design is the relationship between membrane theory and bending theory where shells striving to be structurally efficient will be designed work in membrane action as much as possible

[13]. In this study, all loading experiments show that the studied topology deforms significantly and at a reasonably constant rate prior to inversion. This suggests that the global structure's resistance to displacement is highly reliant on the bending stiffness of the individual members and that it is therefore not only working with membrane action.

In the case of Kagome weaving, the shape of the structure is driven by a set of foundational topological principles for making doubly curved surfaces from straight stock instead of precisely optimising a topology for a given load case. Whilst this may be viewed as a structurally inefficient form-finding method, it makes the case for developing typologies of shell structures that are open to a wider variety of design criteria, spatial conditions, and structural function. A further advantage of relying on bending stiffness is the reduction of a structure's sensitivity to fabrication imperfections and the risk of sudden collapse [13].

4.3. Structural analysis

Without any established methods for analysing Kagome structures, the experiments offer a foundation for dimensional analysis and the development of numerical models. Further experimental work and dimensional analysis using larger scale Kagome structures will reveal how effective the experiments in this study are for predicting the behaviour of larger structures and with different materials. If accurate, this validates an intuitive, accessible, and robust method for analysing the design of Kagome structures in the future.

Secondly, the dataset is useful for calibrating a digital numerical model that can be developed for faster design iterations that include cycles of structural validation. The pinned joint experiments can be used to calibrate an initial numerical model, since this connection type is significantly less complex and heavy to model digitally. Further work can embark on the structural computational modelling of interlacing.

5. Conclusion

In this paper, we investigate the structural behaviour of woven Kagome lattices through physical model experiments, examining the influence of member stiffness and connection type on displacement behaviour under distributed and asymmetric loading. The results demonstrate that increased member stiffness through cross-sectional geometry and/or Young's modulus reduces global displacement and increases resistance to inversion. Comparison between samples with equivalent cross-sectional area but differing proportions further suggests that member depth contributes more significantly to global stiffness than width.

The experiments also revealed substantial variation in displacement patterns and buckling modes between replicates, highlighting the sensitivity of shell-like structures to imperfections and loading conditions. The comparison between interlaced and pinned intersections showed that pinned configurations exhibit approximately three times greater stiffness than purely interlaced connections. This relationship requires further study to determine how interlaced behaviour translates to other scales and materials.

Beyond the specific results, this work demonstrates the value of physical model testing as a method for developing empirical understanding of novel structural typologies prior to establishing validated numerical models. The experimental dataset provides an initial foundation for future dimensional analysis, calibration of computational models, and larger-scale investigations using alternative materials. Further work should explore the effects of scale, orthotropic materials, friction coefficients, and interlacing geometry to further assess the applicability of woven Kagome structures as architectural shell systems.

Acknowledgements

This research was carried out as part of the Kagome Architectures project, supported by the Carlsberg Foundation under the Semper Ardens Accomplish programme, grant agreement No. CF23-1255. The authors would like to thank Christopher Williams for his ongoing helpful guidance in our study of structural lattices.

References

- [1] P. Ayres *et al.*, ‘Weaving the Shimoni Cave: Amplifying Craft Practice Through Computation’, in *Fabricate 2024: Creating Resourceful Futures*, Copenhagen: UCL Press, Apr. 2024, pp. 284–291. doi: 10.2307/jj.11374766.39.
- [2] P. Ayres, A. G. Martin, and M. Zwierzycki, ‘Beyond the basket case: A principled approach to the modelling of kagome weave patterns for the fabrication of interlaced lattice structures using straight strips.’, presented at the Advances in Architectural Geometry, 2018, pp. 72–93.
- [3] Marc Leyral, Quentin Chef, Tom Bardout, Romain Antigny, and Alexis Meyer, ‘Kagome Project: Physical and Numerical Modeling Comparison for a Post-formed Elastic Gridshell’, *Journal of Civil Engineering and Architecture*, vol. 16, no. 4, Apr. 2022, doi: 10.17265/1934-7359/2022.04.004.
- [4] D. A. Lagueche, ‘Development and assessment of a spherical cap timber gridshell with compound beam sections’, presented at the International Association of Shell and Spatial Structures, 2024.
- [5] G. Song and B. Sun, ‘Design and mechanical behavior of hyperbolic weaves with naturally curved ribbons’, *Scientific Reports*, vol. 15, no. 1, p. 13848, Apr. 2025, doi: 10.1038/s41598-025-98520-z.
- [6] H. Shinohara and T. H. P. Chan, ‘A computation design method for architectural artifacts adapted from traditional Kagome bamboo basketry techniques’, *Frontiers of Architectural Research*, vol. 13, no. 2, pp. 249–264, Apr. 2024, doi: 10.1016/j.foar.2023.11.007.
- [7] R. Mesnil, C. Douthe, O. Baverel, and B. Léger, ‘Linear buckling of quadrangular and kagome gridshells: A comparative assessment’, *Engineering Structures*, vol. 132, pp. 337–348, Feb. 2017, doi: 10.1016/j.engstruct.2016.11.039.
- [8] B. Addis, “‘Toys that save millions’ – a history of using physical models in structural design”, *The Structural Engineer*, vol. 91, no. 4, pp. 23–37, Mar. 2013, doi: 10.56330/UUCG3306.
- [9] B. Addis, ‘Physical modelling and form finding’, in *Shell structures for architecture: form finding and optimization*, S. Adriaenssens, P. Block, D. Veenendaal, and C. Williams, Eds, London New York: Routledge/ Taylor & Francis Group, 2014, pp. 33–43. doi: 10.4324/9781315849270.
- [10] E. Buckingham, ‘On Physically Similar Systems; Illustrations of the Use of Dimensional Equations’, *Phys. Rev.*, vol. 4, no. 4, pp. 345–376, Oct. 1914, doi: 10.1103/PhysRev.4.345.
- [11] I. Liddell, ‘Frei Otto and the development of gridshells’, *Case Studies in Structural Engineering*, vol. 4, pp. 39–49, Dec. 2015, doi: 10.1016/j.csse.2015.08.001.
- [12] E. Happold and I. Liddell, ‘Timber lattice roof for the Mannheim Bundesgartenschau’, *The Structural Engineer*, vol. 53, no. 3, Institution of Structural Engineers, London, pp. 99–135, 1975.
- [13] C. J. K. Williams, ‘What is a shell?’, in *Shell structures for architecture: form finding and optimization*, S. Adriaenssens, P. Block, D. Veenendaal, and C. Williams, Eds, London New York: Routledge/ Taylor & Francis Group, 2014, pp. 21–31. doi: 10.4324/9781315849270.
- [14] P. Ayres, J. You-Wen, J. Young, and A. G. Martin, ‘Meshing with Kagome Singularities’, presented at the Advances in Architectural Geometry, 2021, pp. 188–207.
- [15] C. R. Calladine, ‘Buckling of shells: non-classical analysis’, in *Theory of Shell Structures*, 1st edn, Cambridge University Press, 1983. doi: 10.1017/CBO9780511624278.