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The influence of module quantity on the curvature of 3D chain mail structures

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Abstract

This research investigates the impact of the number of modules on the geometry of cantilevered chain mail structures, with a focus on their capacity to achieve stable, self-supporting forms. By integrating physical prototyping with digital analysis, the study examines the geometric profile, intermodular spacing, and dimensions of cantilevered chain mail beams constructed from 3D-printed, interlocking skeletal cubes. Findings demonstrate that the cantilevered beams' curvature is mostly characterised by Catenary curves and identify a 'stability threshold', a minimum number of modules in the beam where a degree of dimensional stability is reached. This study paves the way for future research into the application of chain mail structures in architecture. Namely, it deepens our understanding of the relationship between modules and the resulting geometry of the chain mail structure, building a foundational understanding that facilitates predictive design and simulation necessary to implement architectural scale chain mail structures. This contributes to the innovative application of modular architectural systems, aligning with principles of sustainable and ethical design.

Keywords: Chain mail structure, interlocking assembly, modular construction, curved structure, geometric design, architecture design, curve fitting, form finding.

1. Introduction

1.1. Chain mail reinvented: a new form of structural design

Chain mail has undergone a remarkable transformation from its origins as a medieval protective garment composed of interlinked metal rings to becoming a modern, versatile modular system. Historically utilized across Europe, Africa, and Asia from the 9th to the 14th centuries, its modular geometric adaptability continues to play a significant role in its long-standing functionality to date. In the last two decades, the advent of 3D printing technology has enabled the creation of '3D chain mail' with diverse module shapes. This innovation has not only enhanced chain mail structures' load-bearing capacity, stiffness, and impact resistance while retaining their flexibility (Wang et al. [1], Xu et al. [2]) but also broadened its application scope. It now includes fields such as wearable technology, medical devices (Engel and Liu [3], Ploszajski et al. [4], Ricotta et al. [5]), soft robotics (Ransley et al. [6]), lunar mobility structures (Radziszewski et al. [7]), and notably, architecture (Wang et al. [1]). Specifically, within the architectural domain, chain mail is now recognized for its potential as an adaptive building skin (Borhani and Kalantar [8], Borhani and Kalantar [9]) and as a structural fabric for crafting versatile, transportable structures, such as pavilions or bridges (Wang et al. [1]).

The evolution of chain mail highlights its transformation from a historical material system into a contemporary example of structural design innovation with high relevance to today's architectural demands and ethical construction practices. Through its design and constructional modularity, chain mail aligns with contemporary design sensibilities by promoting functional shape reconfiguration, resource-efficient mass production, and cycles of module repairs, all while weaving form with function through simple, repetitive patterns. Yet, as we delve into the realms of architectural applications for chain mail, a gap emerges in our understanding of how the quantity and configuration of modules influence the form and stability of chain mail structures. This complexity is further accentuated by the jamming behaviour observed in the 3D chain mail structures —where geometrically constrained contacts between modules generate sufficient friction and stiffness to prevent movement and ensure stability (Jaeger [10], Matsushita et al. [11]). The lack of a deep understanding of this intricate interplay among modules, which dictates the structural form and its stability, presents a crucial challenge in the predictive design and practical application of chain mail in modern architecture.

1.2. Research problem and aim

Despite chain mail's considerable potential, research into practical architectural applications faces significant challenges. The complexity and indeterminacy of chain mail structures, along with the scarcity of existing studies, hinder the immediate use of mathematical, geometrical, or numerical methods for modelling and simulating their behaviour accurately in the digital space. This condition necessitates an initial empirical approach through physical experimentation to gather essential data.

Accordingly, our research adopts a systematic, experimental approach to explore the relationship between module composition and chain mail geometry within the architectural context. It specifically examines chain mail structures made of planar, modular assemblies of 3D interlocked skeletal cubes, which can be reversibly constructed into self-supporting, curved beams via a jamming mechanism. Previous research has highlighted the significant impact of module actuation and positioning in defining the geometries achievable by such structures (Afif et al. [12]). However, many factors still need to be further considered. Therefore, to deepen our understanding on the matter of module and geometry relationship, this study examines how varying module quantities influences the formation of stable shape configurations in these types of structures.

2. Methodology

2.1. Research approach

As previously mentioned, the complexity of chain mail structures and the substantial knowledge gaps hinder reliable simulations of their behaviours through direct digital modelling. To address this challenge, our research adopts a systematic, experimental methodology, using small-scale physical prototypes for empirical testing and observation. This data is then utilized in digital modelling and numerical computing software for analysis. This approach aligns with the principles of Research-Through-Design, which leverages artifact creation and iterative exploration to address intricate research questions (Herriott [13], Redström [14]). Additionally, it is supported by a systematic design method suitable for intricate problem-solving (Stauffer and Pawar [15], Battistoni et al., 2019 [16]), applicable to the complex nature of chain mail structures.

2.2. Prototype design

In this study, we specifically focused on cantilevered curved beam configurations to demonstrate the unique properties of modern 3D chain mail structures—improved load-bearing capacity, stiffness, and impact resistance while maintaining flexibility. Building upon previous research on 3D chain mail structures (Afif et al. [12]), the design of the prototype curved beam in this study retains the same building block design as the prior work. This consists of 3D skeletal cubes with external dimensions of 20 x 20 x 20 mm and a rectangular cross-section of the cube's beam measuring 4 x 4 mm, resulting in a beam thickness-to-length ratio of 1:5 (Figure 2).

The cantilevered curved beam, supported at only one end, serves as an ideal design for preliminary testing. This is because it demonstrates the unique self-supporting qualities of 3D chain mail while also simplifying curvature to a single plane (XY plane) necessary to understand before analysing curvature in multiple planes that arise with chain mail surface. To allow for a clear, systematic examination of how the quantity of interlocking modules affects the structural form, prototypes with incrementally increasing module counts were developed. In total, six structural variations were observed, with each prototype designed to increase by two modules at each stage, enabling us to record gradual shape changes in the structures. However, as shown in Figure 1, no curvature was observable in the first variation, and by the sixth variation, the curved beam touched the ground, eliminating the cantilever effect. Thus, as dictated by the natural form-finding process of the structure, only structure variations 2 to 5 were analysed in detail.

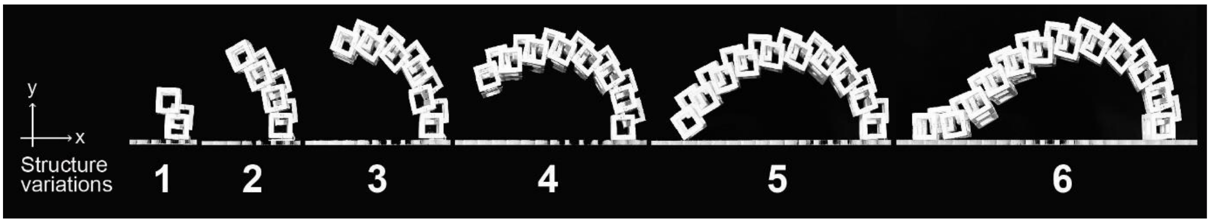


Figure 1: Six cantilevered chain mail beam variations distinguished by interlocked module count. Only Variations 2 to 5 are analysed due to Variation 1's lack of observable curvature, and Variation 6's ground contact negates its cantilevered nature.

2.3. Testing procedure

To form the self-supporting cantilevered curved beams, the initially flat, strip-like structures are rotated by the last modules at one end of the beam and secured to a platform. This action triggers subsequent modules to lift, following the principle of mechanical actuation, which involves inducing designed instabilities for temporary or permanent deformations (Xia et al. [17]). The resulting curvature is a combined effect of the structure's weight —directly dictated by the number of interlocked modules and the total gap between the modules, influenced by the modules' shape and size (Figure 2).

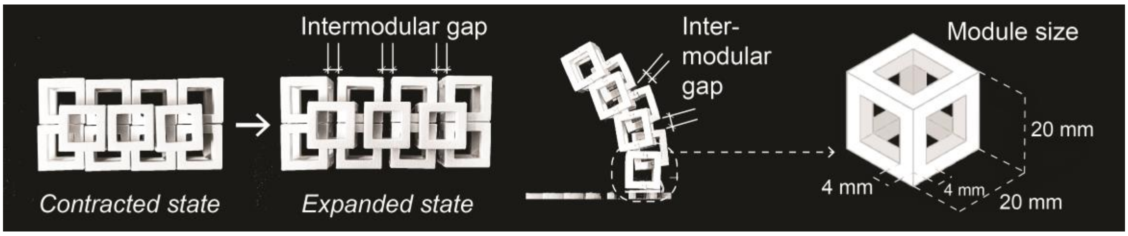


Figure 2: A flat-laid chain mail beam on a platform, with intermodular gaps emerging as the structure expands (left), and the size of the module (right)

To record the test data, we used a structured light-based 3D scanner, specifically the Artec Spider 3D scanner. Data extraction and analysis were performed using Rhinoceros 3D with the Grasshopper plugin and MATLAB software. We evaluated the geometry of the structures through three sets of parameters, that are the structure's overall dimensions of height and length, the mathematical model to describe the structures' curvature, and the variation in intermodular spacing as a measure of curvature adaptability. Details on these parameters and the process of extracting this geometric data from scan results, are discussed in the subsequent Data and Discussion section.

3. Data and discussion

3.1. Evaluation parameters

As mentioned in Section 2.3, this study utilizes three sets of parameters to evaluate the geometry of the observed structures. The following subsections discuss each parameter and its data extraction procedure, focusing on how specific data for each design and evaluation parameter is obtained. Structure Variation 4 is used as an example in illustrating the procedures.

3.1.1. Overall dimensions

The first evaluation parameter is the structure's dimensions, defined by the projected length and height within a 2D space. The length is the distance from the first to the last module along the x-axis, while the projected height is measured from the ground to the apex along the y-axis (Figure 3). This parameter involves data extraction using Rhinoceros 3D software with the Grasshopper plugin, with analysis achievable through any spreadsheet software.

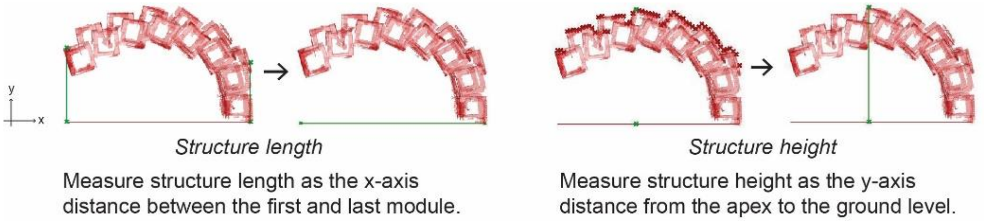


Figure 3: Data extraction focusing on the structure's dimensions by measuring structure length (x-axis) and height from apex to ground (y-axis).

3.1.2. Structure curvature

Then, the second evaluation parameter focuses on the structure' curvature, and which mathematical best describes curvature in each model variations, determined through curve fitting methods. The aim of employing this parameter is to understand the relationship between module count and beam curvature. We contend this understanding is instrumental in guiding the potential architectural applications of chain mail structures, identifying equivalent existing architectural paradigm where 3D chain mail could then be implemented, and determining the necessary mechanical properties for subsequent fabrication materials for the structures in real scale.

To capture the structure's curvature in the XY plane, we extract a series of points from intersections between the structure's scanned mesh and cutting planes at set intervals. These coordinates are then used to plot an identical graph in MATLAB. While the primary data extraction and analysis processes for this parameter are conducted in MATLAB, the initial point extraction is performed in Rhinoceros 3D using the Grasshopper plugin, as illustrated in Figure 4.

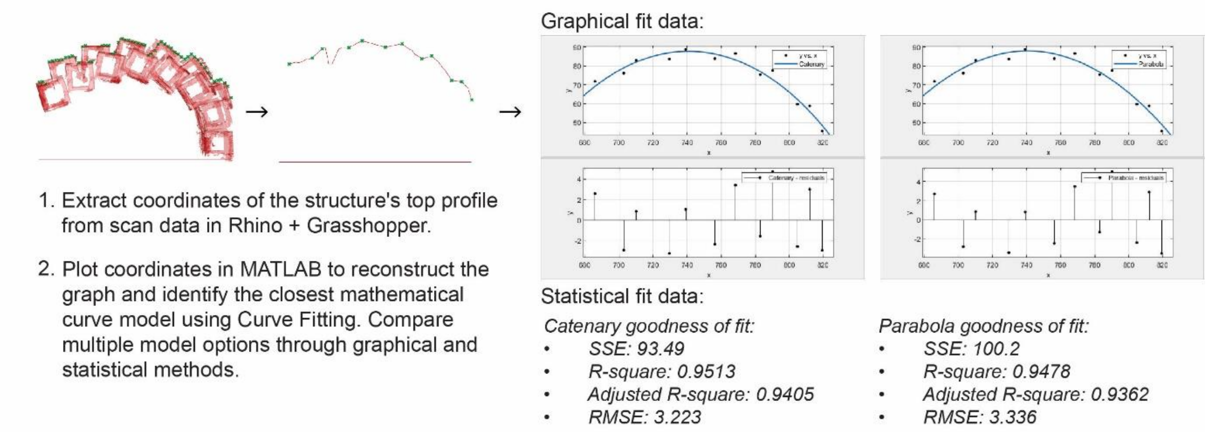


Figure 4: Data extraction method for evaluating the curved structure's geometrical profile, involving point coordinate collection and curve fitting analysis.

3.1.3. Variation in the structure's intermodular spacing

For the last evaluation parameter, we examine the variation in intermodular spacing as an indication of the structure's adaptability to different degrees of curvature. This parameter essentially illustrates the structure's capacity for expansion at the interlocked module sections in curvature, which varies according to the module quantity in the configuration as well as the natural jamming mechanism of the structure.

Data for this parameter are obtained by measuring the angles between interlocked modules at the top or outermost row of the structure (XY plane, refer to Figure 5). The extraction process is conducted entirely using Rhinoceros 3D software and the Grasshopper plugin, while the analysis can be performed in any spreadsheet software.

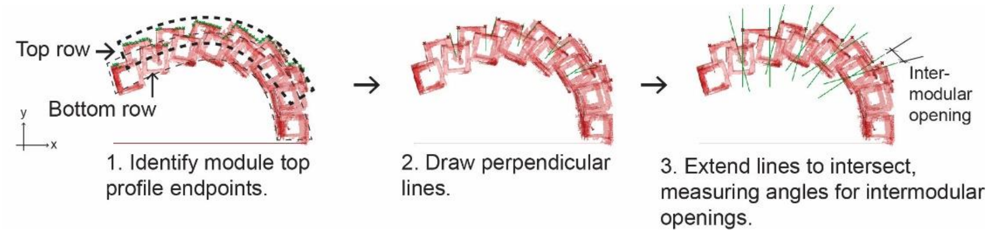


Figure 5*:* Measuring intermodular spacing variation by identifying endpoints and drawing perpendicular lines to calculate opening angles between modules.

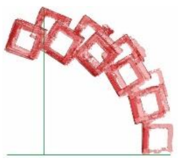
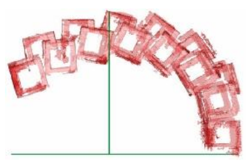
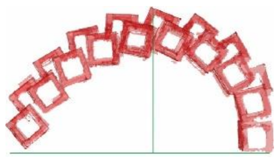
3.2. Data and analysis

This section presents the resulting geometric data for each parameter measured across the four variations of structure tested.

3.2.1. Analysis of overall dimensions

For the first evaluation parameter, we analyse the structure's dimensions based on their projected heights and lengths along the y- and x-axis, respectively (refer to Figure 3 and Table 1).

Table 1: Data on overall dimensions for Variations 2 to 5.

Structure variations	**Visualization**	**Length (mm)**	**Height (mm)**
2		67	76
3		102	91.1
4		141	88.7
5		165	92.8

As can be seen from Table 1, in Structures 3, 4, and 5, the height remains relatively consistent, with variations under 5%. This similarity is due to each having the fifth module in the upper row act as the apex, promoting a stable height. Structure 2, with fewer modules, lacks this apex-forming capacity, resulting in a distinct height profile. This analysis underscores the existence of a module threshold crucial for achieving stable dimensions, particularly in maintaining consistent heights across variations of the cantilevered chain mail beams.

As for the structure's length, there is a clear trend of progressive increase from Structure 2 to 5, influenced by the number of interlocked modules. However, the progressive increase in length is not symmetrical once the structure bend downwards beyond the apex.

3.2.2. Analysis of structure curvature

Next, in analysing the curvature of the structure, our assessment considered a range of model fits for each structural variation. Upon careful examination of both the graphical and statistical fits, we identified two predominant fit models that consistently appeared across all four structural variations, that are the Parabolic fit model and the Catenary fit model. These models provide a framework for characterizing the general shape tendencies of the cantilevered chain mail beam structures produced in our study. The mathematical model for a Parabolic fit (1) is derived from polynomial regression, specifically a second-degree polynomial, while the Catenary fit model (2) is based on non-linear regression, characterized by the hyperbolic cosine function. The equations for each model are as follows:

$$f(x) = p_1x^2 + p_2x + p_3 \quad (1)$$

$$f(x) = a\,cos\left(\frac{x-b}{a}\right) + c \quad (2)$$

Graphical representations of both models' fit for each structure are illustrated in Figure 6, while the statistical fits are detailed in Table 2.

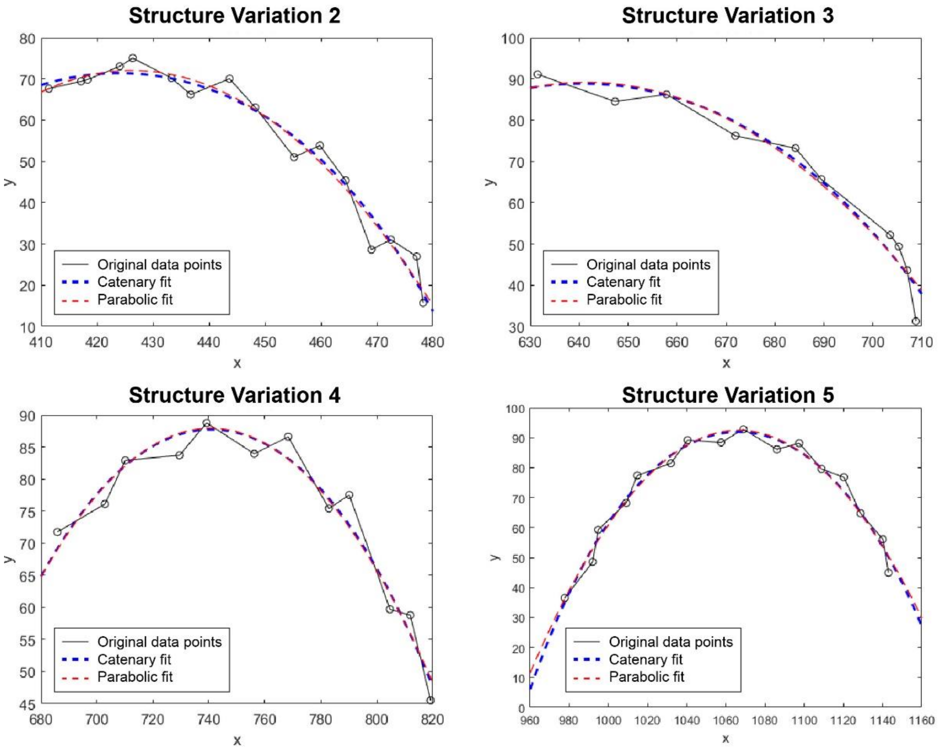


Figure 6*:* Graphical fit data for Variations 2 to 5.

Table 2: Statistical fit data for Variations 2 to 5.

Goodness-of-fit indicators**	**Structure variations/ Mathematical models*** *(Bold text indicates higher value)*							
	2		**3**		**4**		**5**	
	P	**C**	**P**	**C**	**P**	**C**	**P**	**C**
SSE	**182.30**	199.40	171.30	**153.20**	100.20	**93.49**	150.60	**139.90**
R-sq	**0.97**	0.96	0.95	**0.96**	0.95	**0.95**	0.97	**0.97**
Adj R-sq	**0.96**	0.96	0.94	**0.95**	0.94	**0.94**	0.96	**0.97**
RMSE	**3.75**	3.92	4.95	**4.68**	3.34	**3.22**	3.40	**3.28**

*P = Parabola, C = Catenary
**SSE = Sum of Squares Due to Error, R-sq = R-square, Adj. R-sq = Adjusted R-square, RMSE = Root Mean Squared Error

Based on the data presented above, it is evident that Structure Variations 3, 4, and 5 are more closely aligned with the Catenary model, while Structure 2 shows a marginally better fit for the Parabolic model. The distinction lies in Variations 3, 4, and 5, resembling more complete arch forms, as indicated by at least one module extending beyond the apexes of these structures, which is not observed in Structure Variation 2 (see Figure 7, Section 3.2.3). This key difference (the shorter span of the arch not reaching beyond the apex) may explain the observed trends in fit data, with the unique characteristics distinguishing full Catenary curves from Parabolic curves becoming less pronounced over shorter arch spans.
However, beyond the direct fit data, two contextual factors inform our analysis further. Firstly, the primary influence of self-weight on our cantilevered beams echoes the design focus of Catenary arches, which typically bear only their material's self-weight, aiming for efficiency in material use with adequate compressive strength. This approach contrasts with Parabolic arches, designed to accommodate uniform distribution of external loads in addition to the self-weight. Secondly, the inherent asymmetry of our cantilevered beams lends itself more naturally to the Catenary model rather than the Parabolic. Parabolic models, due to their quadratic nature, inherently assume symmetry—a condition not applicable to our structures given their unilateral support.

Henceforth, considering both the fit data and these contextual insights, although all four structures demonstrate flexible compatibility with both Parabolic and Catenary models, we conclude that the geometric profiles of our cantilevered chain mail beams align more closely with the Catenary curve—an inverted hanging chain model—than with the Parabolic curve.

3.2.3 Analysis of intermodular spacing

Finally, in analysing the variation in intermodular spacing within the structures, as detailed in Section 3.1.2, our focus was on the angles between interlocked modules at the top or outermost row of the structure. For comparison, each module is numbered M1, M2, M3 – Mn, where M1 is the module close to the ground module. The corresponding intermodular spacing is named M1-M2, M2-M3,…. (see Figure 7 for the illustration of intermodular spacing and Table 3 for the corresponding data).

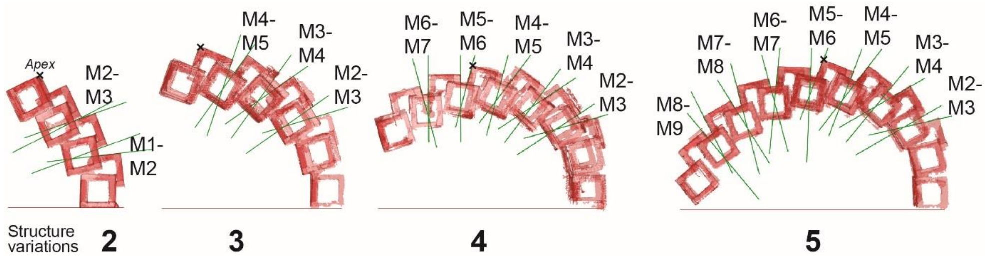


Figure 7: Illustration of intermodular spacing across Variations 2 to 5, with labels added for clarity.

Table 3: Data on intermodular spacing for Variations 2 to 5.

Structure variations	**Intermodular opening angles (degrees)**							
	M1-M2	**M2-M3**	**M3-M4**	**M4-M5**	**M5-M6**	**M6-M7**	**M7-M8**	**M8-M9**
2	13.6	7.8	-	-	-	-	-	-
3	ND*	18.2	19.2	17.3	-	-	-	-
4	ND*	17.4	19.4	22.2	15.3	15.0	-	-
5	ND*	17.0	20.5	16.8	19.0	20.9	17.5	12.9

ND: Not Detectable, due to limited scanning data

The initial segments, specifically the M1-M2s in Structures 3, 4, and 5, faced challenges due to insufficient point cloud density, resulting in their absence from the collected scan data. Despite this, we observed two significant patterns. A notable reduction in the degree of opening for Structure 2, indicating tighter intermodular spacing in a configuration with fewer modules; and relatively consistent opening angles among Structures 3, 4, and 5, with a range of 1.2 degrees in the M2-M3 segment. Moving to the M3-M4 segment, we observed a similarly consistent opening, across all structures, with a range of 1.3 degrees.

Conversely the openings measured in the M4-M5 segment are less consistent, with a range of 5.4 degrees. In Structure 3, limited expansion is seen in its final segment, M4-M5. Then, Structure 4, which has additional modules remaining, shows a brief increase in opening before a downward trend. Lastly, Structure 5, with M4-M5 mid-structure and more modules remaining, exhibits a further trend that is unique only for that structure.

In the final segments, M5-M6 to M8-M9, there is a different behaviour observed in Structures 4 and 5. Structure 4 exhibits a decrease in opening angles; in contrast, Structure 5 shows an increase in opening angles, then a decrease. Overall, we see a trend for consistent intermodular relationship up to M4-M5, which is the last segment before the apex of the curve, but no immediately clear trend can be seen across variations on the downward side (unconstrained side) of the apex.

3.3 Discussion

Our analysis across four observed structures unveils a critical concept of a 'stability threshold' that significantly influences the relationship between module quantity and the geometry of cantilevered chain mail structures, explained through three key findings.

Firstly, a consistent height profile for structures that surpass an apex (Variations 3, 4 and 5) and uniform degree of opening between segments indicate that a stability threshold is reached at a certain module count. This threshold thus suggests reaching of a stable and predictable jammed configuration upon reaching specific module arrangements —in this case, five pairs in the lower row and four in the upper row.

Secondly, all structures show high compatibility with both the Catenary and Parabolic models, yet Structure 2, with its minimal module count, exhibits a slight preference for the Parabolic model. This observation shifts when accounting for specific loading and support conditions unique to cantilevered beams, suggesting that the geometric profiles of these beams should align more closely with the Catenary curve. This indicates that the limited number of modules in Structure 2 might lead to a less precise interpretation of the fitting model regarding the structure's geometry. At the same time the inconsistency in behaviour illustrates the adaptivity in the structure up to the point of stability threshold, where the jamming mechanism stabilize the geometry of the structure, which can provide advantages for form finding.

These findings collectively assert the necessity of a specific module threshold for observing predictable structural behaviours and configurations. The limited module count in Structure 2 and the resultant inability to analyse form-finding behaviours comparable to the other structures underscore the significant influence of module quantity on the predictability of geometrical, dimensional, and adaptability profiles of cantilevered chain mail structures. However, it should be acknowledged that while the resolution of the scanner is 0.1 mm and therefore suitable to the scale of the models analysed, it is possible that inaccuracies in scanned models may have been present.

3.4 Future direction on system scalability

While the initial building blocks used in this study are too small for direct architectural applications, subsequent experiments with prototypes scaled up to ten times larger have shown promising scalability of chain mail structures for building-scale implementations. One of these larger prototypes, constructed from structural-grade pine, successfully formed a self-supporting, saddle-like, doubly curved, cantilevered structure with a span of 1.8 m, a width of 1.2 m, and a height of 1.2 m. This suggests the potential of this chain mail system for use in transportable and reconfigurable pavilions as discussed in Section 1. By maintaining consistent geometrical parameters, structural morphology, and actuation procedures, these scaled prototypes preserved the system's inherent jamming characteristics, as demonstrated by the smaller models (Afif et al. [18]).

To effectively transition to habitable-scale prototypes, future research must extend beyond geometrical scaling. It should involve thorough investigations into the materials and corresponding manufacturing techniques for fabricating skeletal cube modules and explore suitable cladding materials. Additionally, developing technological solutions for integrating these new structural components with existing building systems is essential. Such studies will ensure that larger prototypes not only replicate the behavior of their smaller counterparts but also meet the stringent practical and sustainability requirements necessary for architectural-scale structures.

4. Conclusion

In conclusion, this study successfully deepened our understanding of how module quantity influences the geometry of cantilevered chain mail structures. By integrating physical prototyping with digital analysis, we demonstrated the essential role of module quantity in forming stable, self-supporting structures. Our findings indicate chain mail beams curvature is characterised by Catenary curves under specific conditions and uncover 'stability threshold'. This threshold is reached once a certain number of modules are included in the beam, a pivotal factor for predicting geometry and dimensional stability. As we move forward, these findings open avenues for further exploration of chain mail systems, particularly in designing adaptive and flexible architectural elements that can help us appreciate the way chain mail system respond dynamically to their environment and user needs through their unique adaptability, structural integrity, and aesthetic appeal.

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