Additive Manufacturing of Lattice Metamaterials with Tunable Rate-Dependent Mechanics

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Abstract— **Mechanical metamaterials represent a transformative class of architected solids that leverage geometry-induced deformation to achieve exceptional properties such as high stiffness-to-weight ratios, negative Poisson's ratio, and tunable energy absorption. Periodic lattice structures form the design foundation of these materials, allowing control over elastic modulus, compressive strength, and deformation pathways through topological optimization. In alignment with Industry 5.0, integrating intelligent design, digital manufacturing, and sustainability, these metamaterials enable lightweight and adaptive structures for aerospace, automotive, and defence applications. This study investigates the strain-rate-dependent compressive behaviour of four canonical lattice topologies: Gyroid, Kelvin, Honeycomb, and Octet, fabricated via FDM using carbon-fibre-reinforced nylon. All specimens were printed under identical parameters and tested under uniaxial compression (ASTM D1621) at strain rates of 1, 2, 3, and 4 mm min^{-1}. The results indicated rate sensitivity, with compressive strength increasing at higher strain rates due to viscoelastic stiffening and reduced interlayer relaxation. Among the topologies, the Gyroid lattice exhibited the highest compressive strength, rising from 16.35 MPa to 28.39 MPa with increasing strain rate, followed by Octet (19.90 MPa), Honeycomb (17.49 MPa), and Kelvin (2.02 MPa). The Gyroid's continuous curvature and uniform stress distribution underpins its superior performance, underscoring the critical influence of topology in rate-dependent deformation of additively manufactured metamaterials. These findings highlight the role of lattice topology in governing rate-dependent deformation and demonstrate the potential of additively manufactured mechanical metamaterials in realising geometry-driven property enhancement under the Industry 5.0 paradigm.**

Keywords— Mechanical Metamaterials, Industry 5.0, Additive Manufacturing, Compressive Strength, Lattice Structures

I. Introduction

Metamaterials are engineered materials whose extraordinary responses such as negative Poisson's ratio and superior energy absorption arise principally from their meticulously crafted lattice architectures [1]. Unlike conventional materials, their mechanical behaviour can be precisely tailored through rational topological design, enabling phenomena such as ultrahigh stiffness-to-weight ratios, negative Poisson's ratios, and programmable deformation. Lattice structures, periodic three-dimensional arrays of repeating unit cells, have emerged as a leading paradigm in this field, boasting periodic networks of struts or shells that permit precise tuning of mechanical, acoustic, and thermal properties [2], [3]. Due to this unique architected design, they offer exceptional combinations of low density, high stiffness-to-weight ratios, tunable elastic modulus, and energy absorption, rendering them highly attractive for numerous engineering applications such as aerospace, automotive, robotics, and biomedical engineering [4], [5]. The convergence of digital manufacturing and computational design tools has accelerated the realization of such metamaterials, particularly through additive manufacturing (AM), which allows precise control of microscale geometry and density gradients [6], while also enabling rapid prototyping and digital direct manufacturing - a key enabler under the Industry 5.0 paradigm [7].

Lattice structures can be classified based on their topological configuration and deformation mechanism. According to the Maxwell criterion, expressed as $M = b - 3j + 6$, where 'b' and 'j' denote the number of struts and joints per unit cell, respectively, the mechanical response of a lattice is governed by its structural connectivity. Architectures with $M > 0$, such as the octet-truss, are stretch-dominated systems in which axial forces prevail, leading to high stiffness and strength-to-weight efficiency. In contrast, those with M < 0, including Kelvin and honeycomb lattices, are bending-dominated, deforming primarily through flexural modes that provide lower stiffness efficiency [7], [8]. Beyond these conventional truss-based frameworks, triply periodic minimal surface (TPMS) lattices defined mathematically by zero mean curvature, exhibit a distinct shell-dominated deformation mechanism. Among them, the gyroid structure stands out for its continuous curvature and uniform stress-flow pathways, which effectively minimize localized stress concentrations and delay failure, making it an exemplary representative of TPMS geometries [9], [10].

The rapid evolution toward Industry 5.0 - an era integrating intelligent design, sustainability, and human-centric manufacturing has further accentuated the importance of such geometry-driven materials [11]. Additively manufactured lattices serve as a bridge between lightweight efficiency and functional adaptability, aligning with circular-economy objectives through material efficiency and recyclability. Recent studies have demonstrated the transformative impact of lattice metamaterial design and application, especially in metals, ceramics, composites. For instance, Li et al. fabricated sheet-based Gyroid lattices from 316L stainless steel using selective laser melting, achieving quasi-static compressive strength around 57.6 MPa and dynamic strength exceeding 100 MPa with a specific energy absorption of 27.54 J/g, rising by 28% at higher strain rates, making them ideal for protective and impact-mitigation applications [12]. In another study, Yu at al. employed wire arc additive manufacturing (CMT-WAAM) to produce aluminum truss lattices such as tetrahedral, pyramidal, Kagome, and octet configurations using ER4043 wire, focusing on automated process planning for lightweight, energy-absorbing, and load-bearing aerospace and automotive structures [13]. Similarly, Park et al. designed kelvin lattice structures using Ti-6Al-4V alloy fabricated by selective laser melting (SLM) and analyzed them through finite-element simulations. By varying the relative density (0.008–0.362), the yield strength increased from 0.67 to 51.82 MPa and the Young's modulus from 116 MPa to 11.8 GPa, converging at a 3 × 3 × 3 pattern [14]. These studies highlight the diverse applications of lattice metamaterials ranging from impact and shock absorption to lightweight support, energy dissipation, and adaptive mechanical filtering.

However, most existing research has focused predominantly on metal-based lattices, examining quasi-static compressive behaviour, elastic moduli, and failure morphologies. In contrast, polymeric composite based lattices are emerging as highly promising alternatives to their metallic counterparts. Polymers offer comparable mechanical strength-to-weight ratios coupled with intrinsic benefits such as low density, ease of processing, and design flexibility. When reinforced with short or continuous carbon fibres, polymer composites can exhibit markedly enhanced stiffness, interlayer adhesion, and fatigue endurance [15]. Moreover, polymers possess viscoelastic characteristics that allow tunable energy dissipation, making them suitable for dynamic environments where controlled deformation is essential. Further, the strain-rate-dependent compressive behaviour of polymeric lattices has not been systematically investigated, leaving the complex interplay between rate sensitivity, topology, and viscoelastic response inadequately understood [16].

Accordingly, this study systematically investigates the strain-rate-dependent mechanical behaviour of four canonical lattice metamaterials, namely Kelvin, Gyroid, Octet, and Honeycomb, fabricated using carbon-fibre-reinforced nylon via fused deposition modelling (FDM). These four topologies represent the three fundamental deformation modes: bending-dominated, stretch-dominated, and shell-dominated. Carbon-fibre-reinforced nylon combines high specific stiffness, improved toughness, and superior chemical resistance, rendering it an excellent alternative to unfilled thermoplastics for lightweight yet mechanically demanding applications. The selected material provides a balanced synergy between strength and low density, establishing its suitability for next-generation load-bearing structures where weight efficiency and durability are critical. All lattice specimens were meticulously modelled to maintain identical geometric parameters, including unit-cell size and strut thickness, ensuring equivalent relative density across designs. The fabrication process was executed under tightly controlled deposition conditions to minimize process-induced variability, enabling reproducibility and meaningful topology-based comparison. A systematic series of uniaxial compression tests was then conducted at strain rates of 1, 2, 3, and 4 mm min^{-1}, following ASTM D1621 standard, to evaluate the influence of loading rate on mechanical response. This experimental framework facilitated a comprehensive examination of the interplay between lattice topology and viscoelastic rate sensitivity. The findings offer new insight into how geometric configuration governs strain-rate-dependent deformation in polymer-composite metamaterials, contributing to the design of lightweight, adaptive, and energy-efficient structures tailored for advanced engineering applications under the Industry 5.0 paradigm.

II. EXPERIMENTAL PROCEDURE

A. *Design of Lattice Structures*

The geometric design of architected lattices governs the mechanical response of metamaterials. Four canonical unit-cell topologies: gyroid, octet, honeycomb, and Kelvin were adopted to systematically evaluate topology-driven load transfer and strain-rate sensitivity. Each unit cell was parameterized with a uniform cell length L = 10mm and strut or wall thickness t = 2mm, maintaining an equivalent relative density for cross-comparison. The unit cell of all lattice structures is depicted in figure 1.

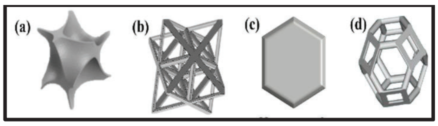

Figure 1: Unit Cell of lattice structures (a) Gyroid (b) Octet (c) Honeycomb (d) Kelvin

The gyroid is a triply periodic minimal surface (TPMS) with zero mean curvature everywhere, generating a continuous, self-supporting network without sharp nodes. Its smooth stress-flow pathways suppress local stress concentration and delay catastrophic strut buckling, which underpins its unusually high specific strength and progressive crushing response compared to conventional strut-based lattices at equivalent relative density [17]. The gyroid topology is defined implicitly by equation 1:

$$sinx \cdot cosy + siny \cdot cosz + sinz \cdot cosx = t_0 \quad \text{eq (1)}$$

where t_0 represents the iso-surface threshold controlling wall thickness. The structure is shell-dominated, hence its stiffness E^* and yield strength σ_y^* scale almost linearly with relative density (ρ^*/ρ_s) where ρ^* is density of apparent (effective) density of the lattice structure and ρ_s is density of the solid base material. Such behaviour stems from membrane-type deformation rather than bending of discrete struts. The gyroid's seamless morphology also provides self-support during FDM printing, avoiding overhang-related distortion. Its high surface continuity and interconnected porosity further render it favourable for multifunctional cores and energy-absorbing scaffolds [18].

The octet lattice (often called the octet-truss) is a stretch-dominated, fully triangulated frame that can be interpreted as a face-centered cubic (FCC) network of struts, wherein each node connects 12 axially aligned members, loaded primarily in axial tension/compression rather than bending. This geometry produces near-linear scaling of modulus and compressive strength with relative density, yielding extremely high stiffness- and strength-to-weight ratios that are difficult to reach with bending-dominated counterparts [19]. For struts of diameter 'd' and unit cell length 'L', the relative density is approximated using equation 2:

$$\frac{\rho^*}{\rho_s} \ \alpha \ (\frac{d}{L})^2 \quad \text{eq (2)}$$

Since axial forces prevail over bending, both modulus and strength scale linearly with density, giving the octet its high specific stiffness [20].

The honeycomb architectures are typically bending-dominated in out-of-plane compression but are extraordinarily tunable through simple geometric descriptors. The honeycomb lattice represents a two-dimensional bending-dominated network, described by cell wall length 'l', thickness 't', and internal angle 'θ' [21]. The relative density for a regular hexagonal configuration is given by equation 3:

$$\frac{\rho^*}{\rho_s} = (\frac{2t}{\sqrt{3}\,l}) \quad \text{eq (3)}$$

while the out-of-plane modulus scales as (equation 4):

$$E_z^* \ \alpha \ (\frac{t}{l})^3 \ E_s \quad \text{eq (4)}$$

The Kelvin lattice is derived from the tetrakaidecahedron, a space-filling polyhedron with predominantly 14 faces that approximates equal-volume partitioning with minimal surface area and is often used as an idealized model of closed-cell or open-cell foams. The Kelvin topology is quasi-isotropic: each node connects struts that share load in multiple directions, which promotes stable plateau formation and relatively uniform energy absorption under multiaxial compression [22]. For struts of diameter 'd' within a unit cell 'L', the relative density is given by equation 5:

$$\frac{\rho^*}{\rho_s} \ \alpha \ (\frac{d}{L})^2 \quad \text{eq (5)}$$

and its stiffness follows equation 6:

$$E^* \ \alpha \ (\frac{\rho^*}{\rho_s})^2 \ E_s \quad \text{eq (6)}$$

The kelvin topology yields a broad, stable stress–strain plateau conducive to energy absorption and mechanical damping.

The gyroid embodies a continuous shell-type architecture ensuring efficient stress flow; the octet provides maximal stiffness-to-weight performance via axial load paths; the honeycomb offers easily tunable deformation; and the Kelvin lattice delivers isotropic energy absorption. By fixing the unit-cell length and strut thickness while varying only the topology, the present study isolates the intrinsic geometric influence on compressive response. The inclusion of these archetypes enables comparison between shell-dominated, stretch-dominated, and bending-dominated deformation mechanisms, providing an integrated perspective on how topology dictates mechanical metamaterial performance.

B. Materials and Fabrication

In this research, gyroid, honeycomb, kelvin, and octet lattice structures were fabricated using Fused Deposition Modelling (FDM) on the Method X system by MakerBot Pvt. Ltd., employing carbon fiber reinforced nylon (NCF) as the feedstock material. The NCF filament is a semi-crystalline composite reinforced with short carbon fibers dispersed within a nylon matrix, offering an elastic modulus of 2300 MPa and an elongation at yield of 1.1%. The presence of carbon fibers significantly enhances stiffness, fatigue resistance, and thermal stability compared to unreinforced nylon, rendering it a high-performance candidate for mechanically demanding lattice architectures. The lattice structures were designed with a fixed unit cell length of 10 mm and a strut diameter of 2 mm, ensuring geometric uniformity across all topologies. The FDM process was configured with a 0.2 mm layer height, 100% infill density, and a linear raster deposition strategy to achieve optimal surface finish and dimensional accuracy. By constraining the unit cell geometry while varying the topology, the study enabled a direct evaluation of how architectural differences between gyroid, honeycomb, Kelvin, and octet lattices govern compressive behaviour and energy absorption under quasi-static loading.

C. Mechanical Testing

The compressive response of the additively manufactured lattice structures was evaluated under quasi-static loading conditions using a universal testing machine (UTM, Instron 8800) equipped with a load cell of 10kN in accordance with ASTM D1621. The specimens were positioned between two parallel platens to ensure uniform load transfer and minimize eccentricity. To examine strain-rate sensitivity, the crosshead displacement rate was systematically varied at 1, 2, 3, and 4 $mm.min^{-1}$. Axial force and displacement data were continuously recorded, enabling the construction of stress-strain curves. Engineering stress was obtained by normalizing the applied load with the projected cross-sectional area, while strain was computed from displacement normalized to the specimen height. The primary parameters extracted included peak compressive strength, effective modulus, and energy absorption, calculated as the area under the stress–strain curve up to densification. The peak compressive strength (σ_p) was taken as the maximum stress prior to the onset of densification. The total energy absorption (W) was calculated as the area under the stress–strain curve up to the densification strain (ε_d) according to equation 7.

$$W = \int_0^{\varepsilon_d} \sigma d\varepsilon \qquad \text{eq (7)}$$

All tests were repeated in triplicate to ensure reproducibility, and average values with standard deviations were reported. Figure 2 illustrates the fabrication and testing process of the lattice structures with the specified parameters.

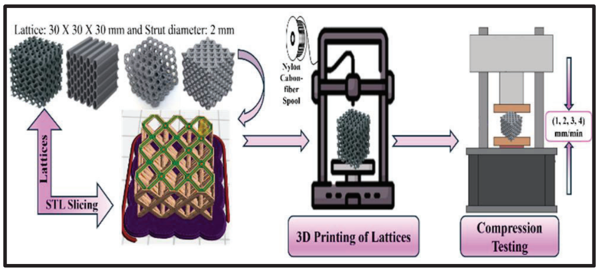

Figure 2: Fabrication and testing process of the lattice structures

III. RESULTS AND DISCUSSION

The stress–strain profiles for the four canonical lattice topologies, Gyroid, Octet, honeycomb, and Kelvin tested at varying crosshead speeds (1 - 4 mm.min^{-1}), illustrate a distinct interplay between topology-driven load transfer and viscoelastic rate dependency of the carbon-fibre-reinforced nylon matrix. The maximum compressive strength in Table 1 reveals a distinct and consistent strain-rate-dependent strengthening behaviour across all lattice topologies.

Table 1: Maximum compressive strength values for structures tested at varying strain rate

	Compressive Strength (MPa)			
	1 mm/min	**2 mm/min**	**3 mm/min**	**4 mm/min**
Gyroid	15.60	16.35	26.16	28.39
Octet	12.77	15.50	17.84	19.90
Honeycomb	9.13	10.58	13.57	17.49
Kelvin	0.86	1.70	1.90	2.02

As the crosshead speed increases from 1 mm.min^{-1} to 4 mm.min^{-1}, each structure exhibited a rise in peak compressive stress, exhibiting the viscoelastic stiffening characteristic of the carbon-fibre reinforced nylon matrix. This enhancement transpired from the time-dependent molecular dynamics of the polymer phase, where higher deformation rates restrict polymer chain relaxation, increase the apparent modulus, and facilitate more efficient stress transfer between the fibre and matrix interfaces. Among the four topologies, the Gyroid lattice consistently demonstrated the highest compressive strength at every strain rate, improving from 15.6 MPa at 1 mm.min^{-1} to 28.39 MPa at 4 mm.min^{-1}, strengthening almost twice. This substantial strengthening underscores the efficiency of the gyroid's shell-dominated load transfer mechanism, in which the continuous curvature and absence of discrete nodes minimize localized bending and enable uniform stress redistribution. The Octet lattice followed a similar ascending trend, with compressive strength rising from 12.77 MPa to 19.90 MPa attributed to its stretch-dominated truss geometry where the load is primarily carried along axial members, thereby maintaining near-linear stiffness scaling with increasing strain rate. However, localized stress accumulation at the node intersections restricts the extent of strengthening relative to the gyroid. Further, the honeycomb structure governed by bending-dominated deformation, also exhibited a pronounced rate sensitivity with its compressive strength increasing from 9.13 MPa to 17.49 MPa, as higher strain rates inhibit elastic buckling and amplify the wall stiffness by limiting viscoelastic relaxation during deformation. Conversely, the Kelvin lattice, characterized by a quasi-isotropic cell arrangement and bending-dominated mechanics, displayed the lowest strength values but maintains a positive trend from 0.86 MPa to 2.02 MPa. Overall, the ascending trend in compressive strength across all topologies corroborates the synergistic influence of geometry and viscoelastic matrix behaviour, where the gyroid and octet architectures, due to their shell- and stretch-dominated load paths, exhibited superior rate responsiveness and mechanical efficiency, while the honeycomb and Kelvin structures, though weaker, displayed enhancements governed by restricted molecular relaxation and enhanced stiffness at elevated loading rates.

The progressive rise in compressive strength values, as detailed in Table 1, culminates at 4 mm.min^{-1} where each lattice demonstrates its optimal load-bearing capability. Correspondingly, the representative stress-strain curves at this rate delineate the deformation sequence, from elastic loading to densification, thereby establishing a mechanistic correlation between the quantitative enhancement in compressive strength and the topology-governed stress evolution within each lattice architecture. The stress-strain responses of the lattices demonstrate distinct deformation pathways as depicted in figure 3. The Gyroid and Octet lattices exhibit the characteristic progression from an initial elastic region through a pronounced plateau to a final densification phase. Whist the Honeycomb lattice exhibited a sharp peak followed by abrupt stress drops linked to wall buckling and shear band formation, and the Kelvin lattice displayed an almost linear plateau development due to its bending-dominated deformation.

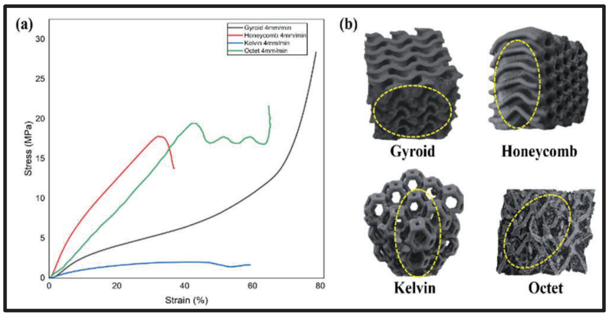

Figure 3: (a) Stress-strain response and (b) corresponding deformation morphologies of lattice structures tested at a strain rate of 4 $mm.min^{-1}$

The gyroid lattice exhibited the highest compressive strength and a continuous stress escalation up to densification without abrupt load drop. The smooth curvature of its triply periodic minimal surface, combined with the intrinsic stiffness of carbon-fiber reinforced nylon, enabled efficient load transfer through the interconnected network, promoting uniform stress distribution and delaying localized failure. The post-compression morphology showed homogeneous layer wise flattening and limited crack propagation, confirming a shell-dominated deformation where stress was absorbed through synergistic bending and stretching of the carbon fiber-filled polymer matrix. In contrast, the honeycomb lattice displayed a steep stress rise followed by a sharp drop (~17.5 MPa), signifying localized buckling and brittle fracture of thin walls. The presence of carbon fibers enhanced stiffness but also induced localized stress concentrations, promoting shear band formation and catastrophic wall folding. The Kelvin lattice, with its open tetrakaidecahedral geometry, exhibited the lowest strength and a nearly linear elastic response governed by strut bending. The composite's limited ductility and fiber–matrix interfacial friction restricted plastic deformation, resulting in the absence of a plateau region or significant energy absorption. Conversely, the Octet lattice exhibited an intermediate yet more stable response (~19.9 MPa) characterized by sequential strut buckling and re-stiffening, as reflected by multiple stress oscillations post-yield. The deformation showed diagonal shear planes and partial node crushing, indicative of stretch-dominated behaviour enhanced by the reinforcing fibers that constrained matrix flow and facilitated progressive densification. The distributed carbon fibers within the nylon matrix acted as stress bridges during compression, enhancing both stiffness and load recovery while mitigating sudden brittle failure. Collectively, the mechanical and morphological analyses reveal that gyroid and octet architectures, in combination with carbon-reinforced nylon, exhibited controlled deformation, high stiffness-to-weight ratio, and superior energy absorption due to their hybrid stretch/shell-dominated mechanisms and strong interfacial load transfer. In contrast, honeycomb and Kelvin lattices, though geometrically efficient, were constrained by bending-dominated modes and interfacial debonding under localized stress. Hence, the synergistic interaction between lattice topology and the carbon–polymer composite microstructure under varying strain rate governs the observed mechanical hierarchy, establishing the gyroid as the most structurally and materially efficient design for high-strength, impact-absorbing applications.

Table 2: Energy Absorption values for structures tested at varying strain rate

	Energy Absorbed (J)			
	1 mm/min	**2 mm/min**	**3 mm/min**	**4 mm/min**
Gyroid	437.33	685.29	775.40	887.44
Octet	139.96	312.09	492.06	617.74
Honeycomb	100.03	129.83	228.99	405.20
Kelvin	17.06	53.75	72.48	90.13

The corresponding energy absorption data (table 2) further substantiates this mechanical hierarchy, with the gyroid lattice exhibiting the highest energy absorption of 887.44 J at 4 $mm.min^{-1}$, followed by the octet (617.71 J), honeycomb (405.20 J), and kelvin (90.13 J) structures. This progression reflects the dominance of stretch- and shell-governed deformation modes in gyroid and octet architectures, which enable sustained load transfer and gradual densification. The enhanced interfacial load distribution within the carbon-fiber-reinforced nylon matrix further amplifies this capacity, ensuring that these topologies dissipate more mechanical energy prior to failure compared to bending-dominated honeycomb and Kelvin counterparts.

IV. Conclusion

Additively manufactured lattice metamaterials (gyroid, octet, honeycomb, kelvin) fabricated from carbon-fibre reinforced nylon exhibited a pronounced interdependence between geometric topology and strain-rate sensitivity, dictating their compressive performance and deformation mechanics. The gyroid architecture, characterized by its triply periodic minimal surface, manifested superior mechanical efficacy through shell-dominated deformation and continuous stress redistribution, yielding a peak strength of 28.39 MPa and energy absorption of 887.44 J at 4 $mm.min^{-1}$. The octet lattice (19.90 MPa and 617.71J) followed with a stretch-dominated response and progressive densification, while the honeycomb and Kelvin structures, constrained by bending-dominated mechanisms, displayed premature wall buckling and lower load-bearing capacity. The viscoelastic stiffening of the nylon matrix under elevated strain rates curtailed polymer chain relaxation, thereby enhancing stress transfer across fibre-matrix interfaces and augmenting rate-dependent rigidity. This synergistic interplay between topology-induced load pathways and the viscoelastic–reinforcement coupling underscores the deterministic role of architecture in defining deformation modes, failure initiation, and energy dissipation. Comprehensively, the findings substantiate that integrating topology optimization with composite additive manufacturing enables precise modulation of strength-to-weight efficiency, viscoelastic hardening, and strain-rate resilience. Such geometry-driven metamaterials provide a transformative pathway toward lightweight, high-impact-resistant, and adaptive structural systems consonant with the Industry 5.0 ethos of intelligent, sustainable, and functionally architected materials.

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