**Unleashing Enhanced Compressive Strength: 3D Printed Octopus-Inspired Suction Cups using topological engineering**

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**ABSTRACT**

Nature's intricate designs and efficient functionality have evolved over millions of years to thrive in challenging environments while minimizing energy consumption and ecological impact. Inspired by nature's strategies, both the manufacturing industry and academic research strive to develop materials and designs that exhibit high strength. The octopus, a remarkable marine creature, exemplifies a complex and adaptive design. It eight arms aligned with numerous tactile suction cups having specialized geometry and cavity. In this study, we employed fused deposition modelling (FDM) printers to model and fabricate octopus-inspired suction cups. We examined different aspect ratios and shapes of cavities, such as cuboids, cylinders, and octopus's suction cup cavity, while maintaining similar outer geometry. The compressive test proved that the inside cavity plays a major role in enhancing strength due to stress distribution and is represented as a robust biomimetic design. Additionally, the finite element analysis (FEA) is developed to corroborate the experimental findings. The statistical validation of the experimental results is achieved through a multilinear regression equation. Our findings demonstrate that the naturally evolved octopus structure exhibits superior compressive strength, enhanced energy absorption, and the ability to generate negative pressure, rendering it highly suitable for gripping, suction, and shock absorption applications.

**Key Words:***3D printing, Nature Inspired, Bio-memetic, Octopus,* *FEA, Compressive strength,*

# INTRODUCTION

The nature evolved in millions of years and optimize the topological design of the objects/living parts to achieve the functionalities 1. The academic and industrial research devoted to mimic the design and functionality of nature existed objects such as robotic arm inspired from the elephant trunk, a 3D printed soft robotic gripper inspired by cabbage curl leaf 2, building block inspired from honey bee wax 3. The layered hierarchical structures in the bamboo, junction of dental enamel, tortoise shells and nacre have inspired to development of components with high fracture resistance/toughness4. All these creature or objects in nature are very complex in design and integrated with the specific functionality. Therefore, the different designs existed in the nature required to mimic and study their functionality and establish the nature rules of design. This can directly help to advance our technology with lowest adverse impact on climate by minimum energy consumption, building high stiff and resilient materials analogous to nature5. Orthopedic implants/prostheses internal design inspired from the nature, which can be more biocompatible and strength equivalent to the natural bone6, 7.

Replicating these complex designs, both at the laboratory and industrial scale, was a challenging task in the past decade. However, it has now become possible using 3D printers8-10. These printers provide robust platforms for printing a diverse range of materials and can mimic complex designs found in nature11, 12. They can incorporate various material properties such as mechanical13, chemical, optical 14, electrical15, etc. Moreover, 3D printers offer sustainability, flexibility, and customization, resulting in minimal waste and almost ready-to-use products with minimal post-processing16.

The current investigation focuses on understanding the topological design function in terms of strength of the octopus tactile suction cups. The octopus, a marine organism inhabiting the ocean, possesses a soft body along with eight arms. These arms are adorned with numerous tactile suction cups, directly contributing to the octopus' mobility and hunting prowess. The collective arrangement of these suction cups enables octopuses to firmly adhere to intricate, rough, or damp surfaces deep within the ocean. Notably, these suction cups exhibit adaptability, conforming themselves to different substrates to establish a secure grip17, 18. While wet adhesion provides a robust and enduring attachment, dry adhesion offers temporary adherence primarily for locomotion purposes. Remarkably, the octopus suction cup combines the advantages of both wet and dry adhesion19. The octopus tentacles suction cup possesses a crucial geometry that grants it the hidden capability to adhere soft, rough, surface in dry and wet surfaces20-24. Shahabi *et al*.25 developed a suction cup design inspired by soft octopus tentacles, incorporating a strain sensor. This innovative approach enables blind exploration and object recognition. The suction cup's micro channels possess the ability to detect angles, directions, and stiffness, allowing for the accurate exploration of object shapes and the orientation of the suction cup itself. Tramacere *et al.26* utilized a casting process to fabricate an elastomeric suction cup. They further enhanced its functionality by employing laser engraving techniques to create grooves on the surface of the sucker. Through their experiments, they discovered that these grooves significantly improved the sticking properties of the suction cup on smooth surfaces. In another study, it was reported that the suction cup design inspired by octopus suction capabilities exhibited remarkable performance in gripping intricate objects. The study found that the octopus-inspired suction cup achieved enhanced grasping forces, with a magnitude of 1.4 times greater in air, 2.4 times greater in water, and an impressive 12.5 times higher in oil compared to conventional suction cups27. In the literature, most articles are related to functional applications of suction cup. However, the architectural design is also a key factor in unlocking the full potential of octopus-inspired suction cups for various practical applications.

Here, the geometry of the octopus's suction cup has been replicated through 3D printing, allowing for an evaluation of its role and establishing the scientific principles behind its geometric design through compressive strength. The experimental results corroborated with modelling to understand the significance of geometry in the functionality of the suction cup.

# MATERIALS AND METHODS

## Variables and Geometry modelling

Solidworks software is used to develop different CAD models of octopus suction cup with different cavity shapes and sizes. For each category three different variables are chosen. Keeping the internal sucker volume of the octopus suction cup constant, the sucker topology is replaced with some different shapes like cuboid, and cylindrical, to understand the difference and importance of the naturally developed complicated architecture of the octopus’s sucker and the mechanical strength of the whole structures as shown in supporting Figure S1. The suction cup was designed with three different height 40mm,30mm and 20mm. Similarly, to have different aspect ratios of the internal suction cups the wall thickness of the same is varied along Y and X directions as shown in supporting Figure S1. Finally, with these variables and models, the CAD files are converted into the compatible 3D printing file format for additive manufacturing of the samples.

## 3D Printing of different structures

Fused Deposition Modeling (FDM) represents a 3D printing technique based on material extrusion. In this study, polylactic acid (PLA) serves as the chosen material for printing all structures. These filaments are drawn into a heating chamber, where the polymer undergoes melting. It then proceeds through a nozzle and is deposited onto a platform to solidify, gradually forming the model layer by layer. Initially, the CAD model undergoes conversion into the Standard Tessellation Language (STL) file format, making it compatible with 3D printers. The Flashforge printer and accompanying software are utilized for slicing and printing the samples. Optimized printing parameters, including feed rate, heater temperature, bed temperature, cross-slide velocity with resolution, and the number of passes, are adjusted according to the selected material to ensure high-quality results. The filament material used in this study maintains a consistent diameter of 1.75 mm and possesses a mass density of 1.27 g/cm³. To facilitate the printing process, the material is heated within the extruder nozzle to a temperature of 215°C. Subsequently, these materials are extruded through a nozzle onto a heated bed set at 50°C. The resulting structures are characterized by a single-layer thickness of 110 µm along the vertical (z-direction) axis and a 100% infill density.

## Compression

To conduct the compression test on the prepared samples, a universal testing machine (UTM) with the specifications of UTM SHIMADZU [AG 5000G] and a maximum load capacity of 50kN was utilized. The compression test was carried out at ambient temperature and atmospheric pressure, with a strain rate set at 1mm/min. For safety reasons, the samples were compressed until the upper and lower jaws of the UTM were 3mm apart.

During the compression test, the machine recorded the load applied to the samples and the corresponding displacement. This data was then used to plot load vs. displacement and stress vs. strain graphs.

## Regression Analysis

Regression analysis was performed to evaluate the dependency of variables of interest and analysis to estimate the quantifiable effect of the independent variables upon the dependent variable. In the present study, the compressive strength (CS) is the output response and the aspect ratios of the octopus sucker are varied by altering the dimensions in the x and y directions (input variables tx and ty), hence there are two independent variables i.e. dimensions of the wall thickness of the suckers. The relationship and dependency of these input and output variables are analyzed by adopting multiple regression analysis (more specifically linear regression analysis) with a confidence level of 95% and a linear regression model is fitted. A total of nine data points (L9 array) is taken into consideration for the regression analysis. The set of data points are shown in supporting Table S2. For statistical analysis purposes, Minitab 17 software is used.

## Finite Element Analysis (FEA)

To validate and visualize the deformation due to compression inside the sucker zone, finite element analysis is performed by using the structural module of COMSOL Multiphysics 6.1. To improve the computational efficiency, the cylinder, and octopus domain is designed in 2D axis symmetry geometry, as shown in supporting Figure S3.

## FEA Materials selection

In the design and development of engineering analysis, material selection is a crucial phase. An incorrect material selection that lacks the necessary strength, ductility, or physical characteristics to support the load may result in a catastrophic collapse. Material selection is entirely based on the experimental work. Two different materials PLA for the octopus and cylinder geometry and structural steel for the supporting block on the top of these geometry has been chosen in this simulation work, supporting Figure S3.The nonlinear elasto plastic properties of these materials are mentioned in supporting Table S5 (A).

## FEA Mesh generation and boundary conditions

The accuracy obtained from an FEA model depends on the finite element mesh used in the geometry. Octopus and Cylinder geometries are divided into 3 domains during meshing based on their curvatures as high curvature requires extremely fine meshing for convergence. Mapped, edge and triangular meshing are used with a total number of 1531 and 2047 elements respectively. Mapped meshing is used in the steel block placed above the octopus geometry. Edge meshing is provided in the edges of the middle domain to trace the curved nature precisely and in the rest of the geometry triangular meshing is incorporated with different mesh sizing. Upper and lower domains have extra fine meshing using element sizes between 0.0021 mm to 0.553 mm whereas, the middle domain contains extremely fine meshing having element sizes between 0.00055 mm to 0.277 mm. A roller boundary condition with normal orientation constraint is applied at the bottom edge of the 2D geometry and a force of 50 kN is applied to the supporting top steel block in the negative z-direction. The boundary conditions and meshing details of the cylinder and octopus structure are shown in Figures S3 and S4 and supporting Table S6.

## Nonlinear strain hardening physics

The elastic behavior of the PLA is defined and characterized by Young’s modulus E = 680 MPa and Poisson’s ratio ν = 0.35. The hardening function σh behaves nonlinearly on the equivalent plastic strain εpe. In Equation 2. H is the linear hardening coefficient, σysf is the saturation flow stress or residual yield stress, and ζ is the saturation exponent. The values of σys0, σysf, H, and ζ are provided in supporting Table S5 (B). The plastic response follows a nonlinear isotropic hardening model with yield stress given by Equation 1.28, 29.

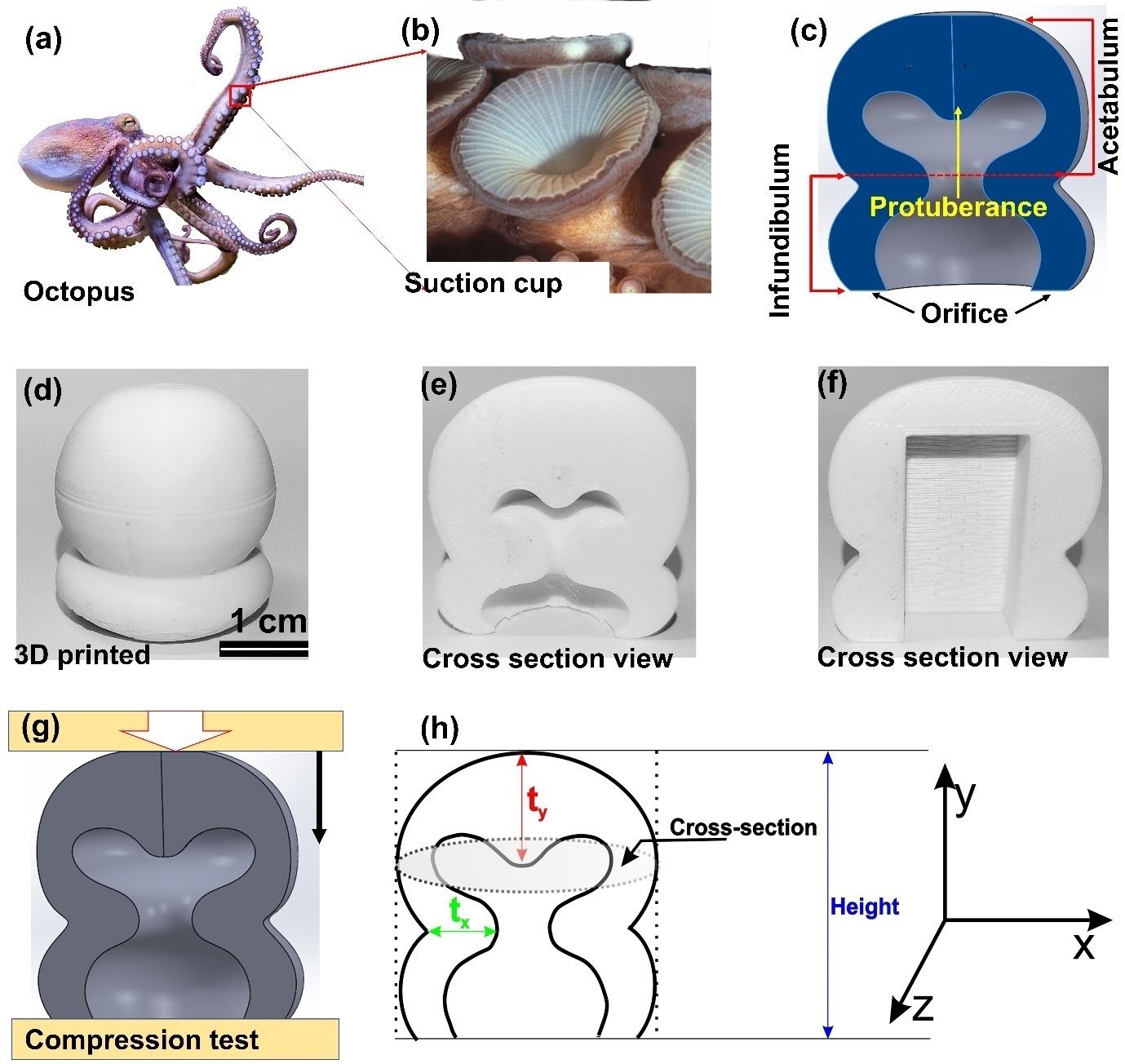
|  |  |  |
| --- | --- | --- |
|  | ys = ys0 + ysf | (1) |

where σys0 is the initial yield stress and σhis the nonlinear hardening function. The latter is defined as

|  |  |  |
| --- | --- | --- |
|  | h(εpe) = Hεpe + (ysf – ys0)[ 1 - eζεpe] | (2) |

# RESULTS & DISCUSSION

The octopus possesses tactile suction cups in eight arms that are highly efficient, allowing them to swiftly move and hunt. These cups are specialized in both shape and internal structure, as depicted in Figure 1(a-c). Various cups were produced with distinct variables, including different cavity shapes and sizes. The cross-sectional view of these cups is illustrated in Figure 1(d-f). As cavity in suction cup and cylindrical cavity were created to unravel the role of cavity and geometry of suction cup by recording the load compression profile.



**Figure 1:** Octopus and their suction cup images (source IIT Kharagpur Arxiv), **(a)** optical photograph of octopus, **(b)** optical photograph of octopas’s suction cup, **(c)** schematic cross section view of octopus’s suction cup, **(d)** optical photograph of 3D printed Suction cup, **(e)** cross section view of 3D printed suction cup with mimic cavity, **(f)** cross section view of 3D printed suction cup with cylindrical cavity, **(g)** Compression test setup, **(h)** schematics of directions.

## Uniaxial Compression test of size and aspect ratio varied samples.

In order to investigate the impact of size on the mechanical properties of octopus suction cups, we conducted compression tests on suction cups of varying heights: 20 mm, 30 mm, and 40 mm. The stress-strain profiles obtained for these sizes were remarkably similar, represented by the nominal stress (force divided by maximal cross-sectional area) versus nominal strain (displacement divided by maximal height). All three sizes exhibited a compressive strength of approximately 24 MPa, as depicted in Figure 2(a). This suggests that the compressive strength of the entire system remains unaffected by changes in size. Despite the octopus possessing suction cups of different sizes on its arms, they possess equal load-bearing capacities. However, smaller suckers are capable of reaching into intricate shapes for capturing and grasping prey, as well as adhering to curved surfaces during feeding and gripping activities. In a separate investigation, we altered the aspect ratio of the octopus sucker by adjusting the wall thickness in the Y-direction (Shown in Figure 1(h)). Specifically, we introduced protuberances. While the elastic zone displayed a consistent slope (representing stiffness or nominal Young's modulus), the plastic zone beyond the yield point exhibited a distinct pattern, as illustrated in Figure 2(b). This observation indicates a noteworthy difference in behaviour in the plastic region. It has been found that the compressive strength of the octopus suction cup increases with higher wall thickness. This is because a thicker wall provides greater resistance against deformation, resulting in enhanced strength. Similar findings have been observed when variations in aspect ratio are made in the X-direction. The highest strength is observed in regions where the wall thickness is greatest in the X-direction, as shown in Figure 2(c). Figure 2(d) presents a comparison of the compressive strength across all the samples. Based on these observations, it can be inferred that, while the strength of the octopus sucker remains independent of size when aspect ratio is kept constant, it is influenced by the shape of the suction cup.

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**Figure 2:** Results obtained from uniaxial compression test **(a)** Size variation of the octopus suction cup keeping aspect ratio constant, **(b)** Aspect ratio changed by changing dimension in the Y direction, **(c)** Aspect ratio changed by changing dimension in the X- direction, and **(d)** Comparison of compressive strength of different samples, **(e)** Stress vs Strain graph **(f)** Compressive strength/ Specific energy comparing octopus suction cup internal geometry with standard geometries

## Uniaxial Compression test of different internal cavities

To evaluate the biomimetic octopus suction cup structure, a comparative analysis was conducted with other cavity structures printed inside the suction cup geometry. The structures considered for comparison included a cuboid, cylinder, sphere, and cone. The aim was to determine the feasibility and effectiveness of accommodating these structures within the octopus suction cup. It was observed that accommodating a sphere or cone structure with the same volume as the octopus's sucker within the limited space of the octopus structure was not practical. This indicates that utilizing a sphere or cone does not efficiently optimize space utilization within the given constraints.

In contrast, the cuboid and cylinder structures were found to be adjustable within the octopus cup structure while maintaining a constant cavity volume. This implies that these shapes offer more flexibility in terms of fitting into the available space without compromising the desired cavity volume.

The comparison highlights the unique and optimized nature of the biomimetic octopus suction cup structure. Its design allows for efficient space utilization and the creation of an effective cavity, which may not be achievable with alternative geometries such as spheres or cones. However, it was found that the compressive strength of the octopus with its natural sucker geometry was the highest (24.47 MPa) compared to the cylindrical (16.97 MPa) and cuboidal (16.99 MPa) structures, as shown in Figure 2(e) and (f). Consequently, it can be concluded that the complex and biologically evolved sucker structures of the octopus exhibit exceptional performance when compared to other available cavity geometries, while, maintain outer geometry similar, in all cases.

## Specific Energy Absorption (SEA) of different internal cavities

To evaluate the energy absorbed by the different structures (octopus, cuboid, and cylinder) at an 8% strain value, the area under the stress-strain curve for each sample was calculated. It's important to note that all structures were modelled with a constant internal cavity volume. Since the outer dimensions were also kept constant, the overall mass of the octopus, cuboid, and cylinder samples was found to be the same, measuring 8223.56 mg, with a volume of 8853.47 mm³. This results in an estimated bulk density of the entire structure to be 0.9289 g/cm³. The specific energy absorption (SEA) at the 8% strain value was determined from the graph and summarized in supporting Table S1. The octopus structure exhibited the highest absorbing capability compared to the cuboid and cylindrical structures, as depicted in Figure 2(f). This is attributed to the outer and internal topology, particularly the presence of protuberances. Consequently, when in active mode, the octopus structure has less impact on the overall structure, as energy is absorbed more efficiently and distributed within the structure due to protuberance and Acetabulum arc, and ground support from Infundibulum region. Conversely, the other two structures have a lesser tendency to distribute energy throughout their bodies, resulting in greater impact on the structure. This can potentially lead to structural damage or a reduced lifespan. Therefore, in terms of energy absorption, shock resistance, and impact resistance, the octopus structure outperforms the other two conventional structures. It is worth mentioning that the energy calculations were performed at the 8% strain value, which is the minimum common value among all the structures. Additionally, since this value is half of the maximum strain value, it is possible to observe similar behaviour at 16% strain as well.

## Multiple Linear Regression analysis and prediction model

The regression analysis was performed to establish a correlation between the input variables (tx and ty) and the output variable (CS), with a confidence level of 95%. A total of nine discrete points, covering a wide range of input variables, were used for the experiments. The L9 orthogonal array was employed to create these arrays, with three sublevels for each independent variable. The output-dependent data (CS) were collected during the experiments for further analysis. To assess the quality of the regression model, a residual plot diagram (supporting Figure S2 (a-d)) was examined. It was observed that the residuals follow a nearly straight line, indicating minimal error. Additionally, the residuals are evenly distributed and exhibit a normal distribution, further validating the model's accuracy.

The regression analysis yielded R2 and adjusted R2 values of 0.94 and 0.92, respectively. These values suggest that the selected variables can accurately explain or predict the orientation angle at approximately 94% correctness, with a confidence level of 95%. The remaining 6% of the variation in the data may be attributed to unaccounted variables, such as cavity volume, aspect ratio, environmental factors, and unknown factors.

The details of the regression analysis, including coefficients and statistical significance, can be found in supporting Table S3. A linear model was fitted for all the variables. The resulting regression equation is as follows:

|  |  |  |
| --- | --- | --- |
|  | **CS = -15.87 + 1.45\* tx + 0.99\* ty** | (3) |

where,

CS= Compressive strength (MPa).

tx= Octopus sucker wall dimension in X-direction in mm.

ty = Octopus sucker wall dimension in Y-direction in mm.

It is obvious from the equation that both tx and ty are positively related to CS. For example, if the dimension in tx is increased by one unit, the CS will increase by ~1.45 units, keeping the ty constant. Similarly, by increasing ty by one unit, the CS will increase by ~0.99 units while keeping the tx constant. On the other hand, theoretically, the CS is -15.87 MPa if all the input variables are kept at zero values which is practically not feasible. Out of two independent variables, the tx is found to be more significant (tx p(0.000196) ≤ 0.05 and ty: p(0.00148) ≤ 0.05).

## FEA Results

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**Figure 3**: FEA compression analysis of octopus suction cup with different shape cavity, **(a)** Initial state in cylindrical cavity, **(b)**displacement distribution in cylindrical cavity, and **(c)** von Mises stress distribution of the cylindrical cavity, **(d)** Initial state of octopus as cavity, **(e)** displacement distribution in cylindrical cavity, **(f)** vonMises stress distribution.

Finite Element Analysis (FEA) was conducted to visualize the deformation behaviour and distribution of von Mises stress within the cylindrical and octopus suction cup structures. While the cylindrical and cuboidal suction domains exhibited similar patterns during compression testing, only the cylindrical domain was used for simulation analysis due to its 2D axisymmetric nature.

A constant load of 50 kN was applied in the negative z-direction on the top block, as shown in supporting Figure S3. A non-linear plasticity model was defined in COMSOL to capture the plastic deformation of the suction cup. The resulting figures present color-coded von Mises stress distributions, ranging gradually from blue to red. The red regions indicate high deformation, while the blue regions represent minimal deformation.

Figure 3 (a) and Figure 3 (c) display the von Mises stress distribution in the initial (0% strain) and final (16% strain) states, respectively, for the cylindrical suction domain. The upper half of the suction cup experiences higher stress compared to the lower half. Interestingly, the von Mises stress distribution in the upper half domain resembles the shape of the naturally occurring internal cavity of an octopus, as highlighted in Figure 3 (c).

In the case of the octopus suction cup, the von Mises stress is distributed throughout the domain, as depicted in Figure 3 (d-f). The maximum stress value in the octopus suction cup reaches 24.4 MPa at 16% strain. The higher compressive strength value and higher stress distribution in Protuberance area to Acetabulum area, while Infundibulum stand but less stress, indicate that the octopus structure possesses better structural robustness. The top protuberance of the octopus structure contributes significantly to its overall stability, as shown in Figure 3 (d) and the two arcs (marked in Figure 3e) or circular ark in 3D structure experience higher stress and capable to absorb energy due to structure. The protuberance provides additional support and interlocks with the upper portion of the side walls, enhancing the load-bearing capacity of the octopus’s structure. Such interlocking is absent in the case of the cylindrical suction cup and there is absent of arc to facilitates more energy absorption.

Figure 3 (b) and (e) illustrate the final states of deformation for the cylindrical and octopus suction cups, respectively. The attached videos provide animations of the compression process for both structures (movie-S1 and movie-S2). It can be observed that at 16% strain, the cylindrical structure experiences more stress concentration zones compared to the octopus structure. This suggests that the octopus’s structure may have superior shock/load absorbing capacity at a specific deformation compared to its cylindrical counterpart.At higher loads, the lower walls of the top protuberance make contact with the upper portion of the side walls of the octopus, as indicated in Figure 3 (e). This interlocking mechanism provides additional support to the entire structure, resulting in a higher load-bearing capacity compared to the cylindrical suction cup. Although the internal cavity volume of both structures is the same, the internal surface area of the octopus suction cup (1051.78 mm²) is greater than that of the cylindrical suction cup (804.24 mm²). This results in a higher specific surface area-to-volume ratio in the octopus suction cup. The larger surface area allows for more efficient air pumping, enabling the octopus suction cup to create higher negative pressure and thus provide a higher load-carrying capacity.

The understanding of the suction capability of the octopus structure is crucial for various engineering applications, such as gripping or lifting operations of high load and endurance with high holding time. The stress-strain plots obtained from experimental testing for the elasto-plastic range were compared with the numerical stress-strain plots obtained from the simulations of the cylindrical and octopus suction cups, as shown in Figure 4 (a and b). The FEA results were found in accordance with the experimental values, with a 3% error value.

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**Figure 4**: **(a)** and **(b)** Comparison between experimental and numerical results of cylindrical and octopus as suction cup cavity respectively, and von Mises stress distribution along the **(c)** Inner curvature and **(d)** Outer curvature of cylindrical and octopus suction cup.

To quantify the von Mises stress distribution within the octopus and cylindrical suction cup, various parameters were calculated and presented in Table S4. These included the range, maximum, minimum, average, and standard deviation of the von Mises stress distribution along the inner and outer curvatures of both structures. Figures 4 (c) and (d) show illustrate the von Mises stress distribution along the inner and outer curvatures of the octopus and cylindrical suction cup, respectively. The standard deviation values for the von Mises stress distribution were determined to be 5.37 MPa and 5.10 MPa for the inner and outer curvature of the octopus suction cup, and 3.62 MPa and 4.30 MPa for the inner and outer curvature of the cylindrical suction cup, respectively.

Upon analyzing the stress distribution, it was observed that the inner suction cup of the octopus structure exhibited higher von Mises stress values at specific locations. The maximum von Mises stress value of 19.8 MPa was identified near the 2 mm mark of the inner arc length, as depicted in Figure 4 (c). In contrast, in other regions, the stress distribution values were lower than the average von Mises stress value. These regions can be termed as stress-relieving domains, as they have the capacity to withstand higher loads compared to the mean stress value. Similarly, the outer suction cup of both the octopus and cylindrical structures displayed similar geometry, with the maximum von Mises stress value occurring near the 2.5 mm mark of the outer arc length, as illustrated in Figure 4 (d).

The presence of stress-relieving domains within the octopus suction cup structure is of utmost importance as they play a critical role in enhancing its stability. Compared to the cylindrical suction cup, the octopus suction cup demonstrated a higher number of stress-relieving domains, particularly in the inner domain. These stress-relieving domains enable the octopus suction cup to withstand higher loads than the average stress value, showcasing its ability to effectively distribute and alleviate stress concentrations. By offering stress relief, these domains significantly contribute to the overall resilience and load-bearing capabilities of the octopus suction cup. They help to mitigate the adverse effects of stress concentrations and ensure the structural integrity of the suction cup even in demanding conditions. The presence of a higher number of stress-relieving domains in the octopus suction cup is a testament to its superior design and optimized performance, making it a highly reliable and robust structure.

# CONCLUSIONS

The nature evolved structure always due to some purpose and linked specialized functions. The complex structure of the octopus suction cup, with its localized stress distribution due to the presence of protuberances, makes it more robust compared to other standard cuboidal and cylindrical geometries. This robustness allows for higher loads, efficient removal of internal pressure, and maximized adhesion. The specific energy absorption of the octopus as cavity structure is 61.38% and 49% higher than that of the cuboidal and cylindrical suction cups, respectively. Additionally, the octopus structure exhibits better compressive strength than the other two structures. The elastic modulus or Young's modulus, being a material property, does not significantly change with variations in the size of the octopus suction cup structure. The mechanical properties of the entire system are not influenced by the size of the suction cup. However, altering the aspect ratio (shape) in either the X or Y direction does affect the compressive strength of the structure. A higher aspect ratio in the loading direction leads to higher compressive strength. The sidewall thickness (tx) has a more pronounced effect (64.61%) on increasing compressive strength compared to the upper wall thickness (ty) of the octopus structure (30.67%), as validated by statistical analysis. This observation is also evident from the FEA analysis, which shows that the upper wall region undergoes more deformation when a load is applied. The results obtained from the finite element analysis (FEA) simulation were found to be in good agreement with the experimental data, validating the accuracy and reliability of the simulation. Under compressive loads, structures tend to distribute stress in a manner that resembles the shape of an internal octopus's cavity. This observation indicates that the naturally evolved structure of an octopus is highly optimized to withstand maximum compressive loads and generate significant negative pressure, which is advantageous for gripping objects. The presence of stress-relieving domains within the octopus suction cup, along with its higher specific energy absorption compared to the cylindrical suction cup, highlights its superior shock-absorbing characteristics. These findings have important implications for the design of optimized structures for various load-bearing actuators and shock-absorbing applications. By studying the unique features of the octopus suction cup, engineers and designers can gain insights into developing innovative structures that can effectively withstand and absorb shocks, opening up possibilities for advanced applications in various industries.

**ASSOCIATED CONTENT:** Movie S1: Von Mises stress distribution in Octopus suction cup with as mimic octopus’ cavity; Movie S2: Von Mises stress distribution in Octopus suction cup with cylindrical cavity. Figure S1-S7 in supporting information file.

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