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Material Impact on Performance of Suction Cups: A Finite Element Analysis

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Abstract: The pivotal role of suction cup handling systems within various industrial and commercial applications, notably in the lifting and manoeuvring of glass window panels and the secure retention of specimens, is underscored by myriad practical implementations. The present research endeavours to meticulously design and rigorously assess the efficacy of suction cup holding systems, employing Catia design software for the creation of the CAD design and utilising the ANSYS simulation package for structural analysis. Particular attention is accorded to the investigation of the suitability of disparate materials for the suction cup, specifically emphasising Nitrile Butadiene Rubber (NBR) and polyurethane, whilst the plate material undergoes examination utilising a carbon fibre composite. Contrastive assessments, grounded in parameters such as stress, deformation, and equivalent elastic strain, are elucidated for these varied material applications. Preliminary findings indicate that, amid numerous suction cup diameters explored, a 141 mm diameter manifests the lowest equivalent stress (ES), whilst a diameter of 118 mm reveals the maximal ES. A 141 mm diameter emerges as optimal in suction cup design and, to minimise deformation, polyurethane rubber (PR) is identified as the most propitious material. Pertaining to the suction cup body, carbon composite material (CCM) is delineated as the pre-eminent selection, offering an enhancement in the strength-to-weight ratio that is notably superior when compared with a carbon steel suction cup apparatus.

Keywords: Suction cup; Finite Element Analysis; Composite materials; CAD modelling

1 Introduction

Suction cups, harnessed for their ability to utilize negative fluid pressure, adhere to non-porous surfaces, securely positioning objects [1]. When contact is made with a surface, air or water is expelled from within the cup, engendering a pressure differential between the internal and external environments, and thereby enabling firm attachment [2]. The elastic properties of suction cups, as depicted in Figure 1, facilitate a reversion to original form upon the removal of external pressure.

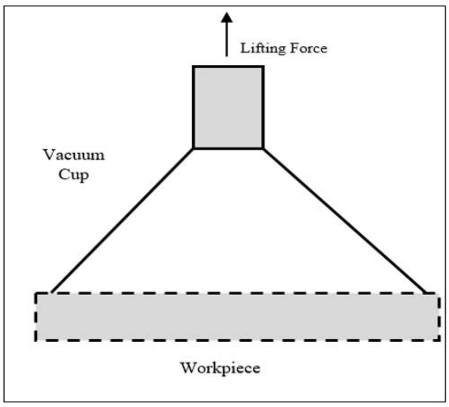

Figure 1. Vacuum pump pressed against workpiece [3]

The adherence duration hinges on the fluid re-entry time into the cavity formed between the cup and the surface. Complete suction is achieved when the internal cavity pressure equilibrates with the external atmospheric pressure. The seal's efficacy is often enhanced utilising vegetable and mineral oils [4]. The research landscape on suction-based gripping mechanisms and vacuum grippers has seen significant advancements and applications in various robotic systems. Several studies have been conducted to explore the potential of these gripping mechanisms and optimize their performance for specific tasks [5]. This paper provides an overview of key research contributions in this field, highlighting the diversity of applications and the challenges encountered. McCulloch and Herath [6] explored the application of gripping mechanisms in conjunction with robotic arms, with a specific focus on suction-based gripping mechanisms. Within the framework of the Amazon Picking Challenge (APC), robots were engineered to manipulate objects with diverse shapes and weights, employing a suction-based gripping approach. This method facilitated efficient item handling by utilizing the power of suction. Kawasaki and Kikuchi [7] centred attention on augmenting suction cup designs for hexapod robot systems, which are specialised for vertical surface ascension. The integration of a passive adhesion mechanism into the suction system not only curtailed material costs but also simplified the overarching design, permitting the 34gm robot to attain a climbing speed of 2.2cm/s.

In scenarios such as the APC, gripper-based suction systems have displayed proficient lifting capabilities with objects that present uniform topologies. Yet, performance deficits were noted when interacting with smaller and topologically inconsistent items, such as spark plugs [8]. Further research has delved into the development and scrutiny of grippers for fan-type climbing robots, highlighting the maintaining of wall adhesion through negative pressure without necessitating sealing [9]. An analytical and experimental exploration of passive suction cups, investigating various phases like pushing, attachment, and detachment, was conducted by Ge et al. [10]. Analytical methodologies ascertained the requisite force for comprehensive attachment, findings which were subsequently validated through experimental endeavours. Emphasis was placed on variables impacting attachment and detachment, such as the vacuum zone area and internal elastic force.

A challenge of air leakage from suction cups on uneven and coarse surfaces was addressed by Schmalz et al. [11]. An analytical equation describing airflow within narrow constrictions was proposed, followed by experimental validation involving the application of soft polyvinyl chloride (PVC) suction cups on sandblasted polymethyl methacrylate (PMMA) plates. Although detachment times largely conformed to analytical prognostications, deviations were observed for root-mean-square (rms) roughness below $\approx 1\mu\mathrm{m}$.

In an examination of adhesion and leakage rates associated with vacuum grippers composed of disparate elastomeric materials, it was found by Tiwari and Persson [12] that notable adhesion was present between NBR and polydimethylsiloxane (PDMS) elastomers. Contrarily, Ethylene Propylene Rubber (EPDM) and Epichlorohydrin rubber (GECO) elastomers demonstrated suboptimal adhesion, culminating in observable water leakage. The magnitude of this leakage was ascertained to be influenced by the water pressure differential (ΔP) across these elastomeric materials. Tinnemann et al. [13] channelled their focus towards high-performance adhesives, drawing inspiration from the fibrillar adhesion pads observed in insects. An innovative method for investigating detachment mechanisms within whole micro-patterned arrays in multiarray suction systems was introduced, with testing revealing a decrement in adhesion forces on both smooth and rough surfaces. Here, interfacial defects were discerned to contribute to suction strength and the detachment process. A concentrated exploration into the progression of vacuum grippers in industrial production systems, specifically pertaining to the manipulation of sheet metal components, was conducted by Gabriel et al. [14]. In the face of a paucity of comprehensive understanding, a model-based strategy, designed to refine the accuracy of the gripping system model while accommodating both maximum anticipated load and gripper deformation, was advanced. This method heralded an impressive 85% augmentation in the energy efficiency of vacuum-assisted handling.

Moreover, a theoretical method for determining optimal placement for two suction cups within a vacuum gripper was employed by Du et al. [15]. The selection of this optimal gripping locale was identified to be contingent upon the object's form and surface texture, with experimental validation affirming the potency of the proposed methodology. Given their multifaceted utility, suction cups are widely deployed across diverse applications. Utilization spans from affixing objects to flat, nonporous surfaces, such as refrigerator doors and glass, to pivotal industrial functions, such as securing ships and holding objects during specific processes like edge grinding. Suction cups permeate even into recreational activities, illustrated by their use in Nerf dart toys and toilet plungers, and extending to audacious exploits like urban climbing on non-porous surfaces.

The current investigation endeavours to elucidate the feasibility of employing varied materials for the suction cup head plate, leveraging Finite Element Method (FEM) analysis. Insights into the structural behaviour of the suction cup under diverse loading conditions, rendered by FEM, facilitate the identification of materials poised to enhance performance. A focus is cast upon the Flat suction cup, owing to its prevalent application for gripping flat and smooth surfaces like glass and plastic. Pursuant to this, the research seeks to navigate through the following queries:

• What avenues exist for enhancing the structural integrity and performance of suction cups within industrial and commercial frameworks?

• How do various materials, such as NBR and polyurethane, influence stress, deformation, and elastic strain experienced by suction cups during use?

A critical examination of the structural analysis of suction cups becomes imperative as it intrinsically influences aspects of safety, efficiency, cost-effectiveness, and material selection, thereby shaping their overarching contribution to industrial and commercial processes. This research aspires to navigate through these facets, seeking to bolster the performance and applicability of suction cups across an array of applications.

The following research objectives have been delineated:

• CAD modelling of the suction cup plate is to be performed, employing design software such as Creo or CATIA to craft accurate virtual representations.

• The suction cup is to be designed to meet the requisite loading conditions for lifting double-glazed windows, ensuring resilience against the necessary forces.

• A suction cup plate, synthesizing three individual suction cups into a singular unit, is to be formulated to amplify stability and load-carrying capacity.

• Finite Element Analysis (FEA) of the suction cup plate, utilizing conventional materials such as natural rubber, will be conducted to ascertain stress and deformation.

• The implications of substituting the suction cup material to NBR will be assessed through a subsequent FEA analysis to compute stress and deformation.

• An additional exploration with polyurethane as the material for the suction cup will be undertaken, evaluating its stress and deformation through FEA.

• The repercussions of transitioning the plate material from a conventional type to carbon fibre composite will be explored by conducting further FEA analysis concerning stress and deformation.

• The research will culminate in the presentation of the most apt material that minimizes deformation and stress whilst ensuring optimal performance.

Evaluating the implications of adopting NBR as a suction cup material is imperative to ensure not only its suitability but also its cost-effectiveness, versatility, and compliance with industry standards. It addresses pivotal concerns pertinent to durability, safety, and sustainability, ultimately serving to optimise suction cup performance across a myriad of applications.

The ensuing discourse is structured into multiple sections, each intended to furnish a comprehensive exploration of the materials employed for the suction cup head plate. Following the introduction and an exhaustive literature review—which encompasses an extensive assessment of various suction cup designs and materials employed in preceding studies—the subsequent section introduces and analyzes the steps embroiled in the FEM analysis in detail. This includes designing, meshing, and defining loads and boundary conditions. Thereafter, the findings of the rigid body dynamic analysis and FEA, inclusive of stress and deformation analysis of the suction cup, are presented. A succinct recapitulation of the results gleaned from FEA analysis, contrasting NBR and PR against conventional materials, is also provided. The ensuing section engages in a comparison and analysis of the results obtained, while the conclusion of the paper is dedicated to summarising findings, proffering future directions, and exploring applications for the identified optimal suction cup material.

2 Methodology

This study unfolds through a bifurcated methodology: CAD modelling and FEA simulation of the suction cup, which are meticulously elucidated within this section [16].

2.1 CAD Modeling of Suction Cup

CAD representations of the suction cup were generated employing SolidWorks design software, wherein the sketching and extrusion tools were manipulated for the creation process [17]. The establishment of a pertinent diameter for the suction cup incorporated considerations of both theoretical and pragmatic scenarios, facilitated by manual computations.

2.1.1 Calculation for the ideal scenario

The suction cup's design was optimized to fortify a load expressed as:

$$F = P \times A \tag{1}$$

where, F represents force, P denotes atmospheric pressure, and A indicates the area of the suction cup.

2.1.2 Real-world measurements

Calculations for the United States (US) imperial units are exemplified as:

$$D = 0.44 \times \sqrt{\frac{\frac{a}{2.2} \times s}{\frac{v}{29.5} \times c}} \tag{2}$$

where, D represents diameter (inches), a indicates mass (lbs), c for the set of cups, v for vacuum (inches of Hg), and s for safety factor (a minimum of 2). For a diameter of 118 mm, the mass is recalculated under actual conditions for use in subsequent FEA simulations.

Metric units' calculations were conducted as follows:

$$D = 11.2 \times \sqrt{\frac{m \times s}{b \times c}} \tag{3}$$

where, D implies diameter (mm), a is mass (kg), c indicates the number of cups, b denotes vacuum in bars (with a standard value of 1.75), and s specifies the safety factor (a minimum of 2). Through the above formula, the mass was computed to be 97 kg. The CAD models of suction cup designs are graphically represented in Figures 2, 3, and 4, respectively.

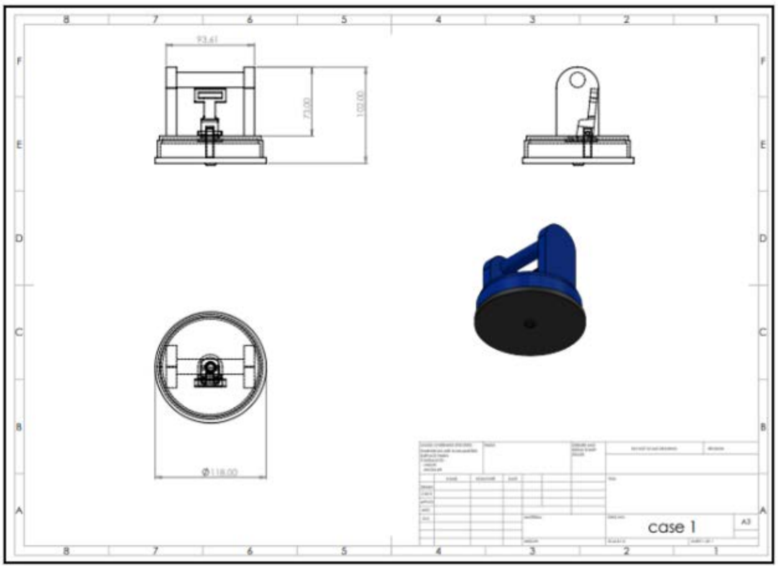

Figure 2. CAD model of design 1

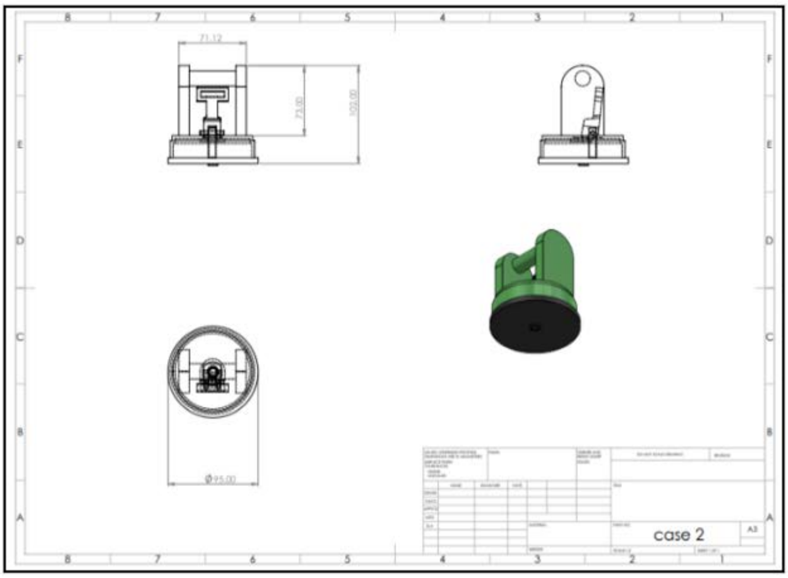

Figure 3. CAD model of design 2

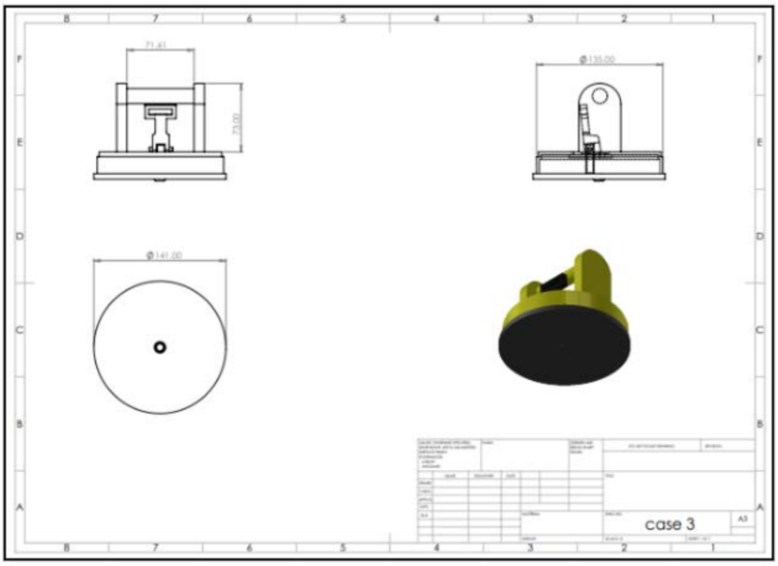

Figure 4. CAD model of design 3

2.2 FEA Simulation of Suction Cup

An exploration into the durability of the suction cup was conducted through the execution of a FEA simulation, wherein structural loads and boundary conditions were meticulously applied to the suction cup, considering real-world scenarios and safety factors. Utilising the ANSYS simulation software package, a meticulous examination and adaptation of various material compositions of the suction cup were undertaken during the FEA simulation process. The subsequent subsections expound upon the different phases of the FEA analysis executed on the suction cup.

2.2.1 Importing CAD design

The CAD schematic of the suction cup was imported into the ANSYS Design Modeler software, ensuring a thorough examination for potential geometrical inconsistencies such as sharp edges or surface irregularities [18]. Figure 5 illustrates the imported suction cup model for referential purposes.

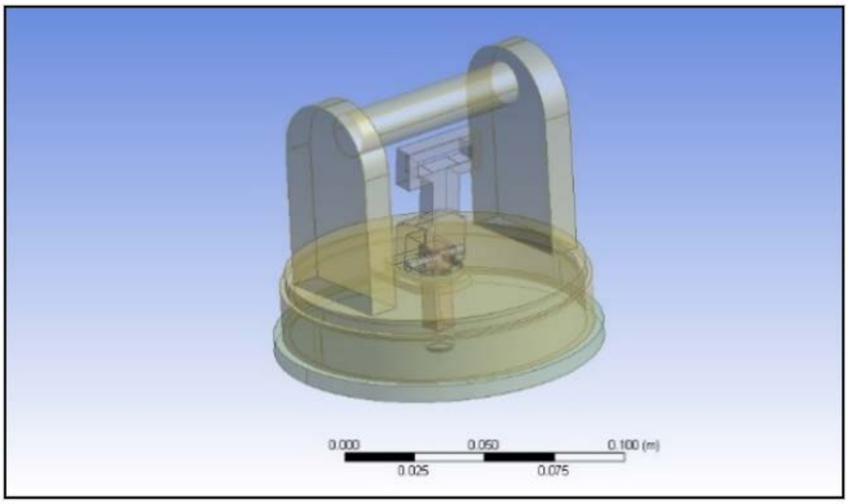

Figure 5. Imported CAD model

2.2.2 Meshing

Meshing of the suction cup model was executed, employing an automatic element selection process. Given the lack of topological consistency in the suction cup geometry, hexahedral element meshing was deemed unsuitable. Tetrahedral elements were instead utilized for the meshing process, as depicted in Figure 6, culminating in the generation of 12,155 elements and 25,597 nodes.

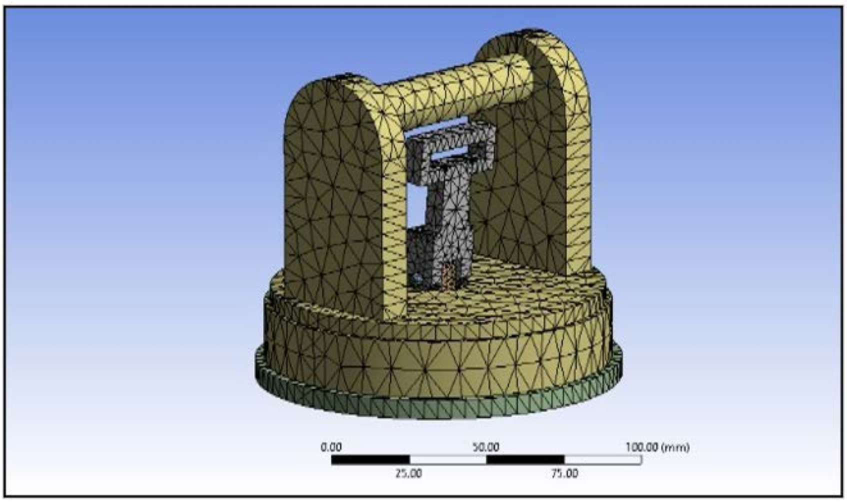

Figure 6. Meshed model of suction cup

2.2.3 Loads and boundary conditions

Loads and boundary conditions were judiciously imposed on the suction cup, with empirical and safety considerations in mind. Displacement support was enforced on the upper cylindrical surfaces, distinctly highlighted in a yellow region as demonstrated in Figure 7. Furthermore, a force of 970 N, reflective of a lifting capacity of 97 kg, was applied to the lower rubber portion.

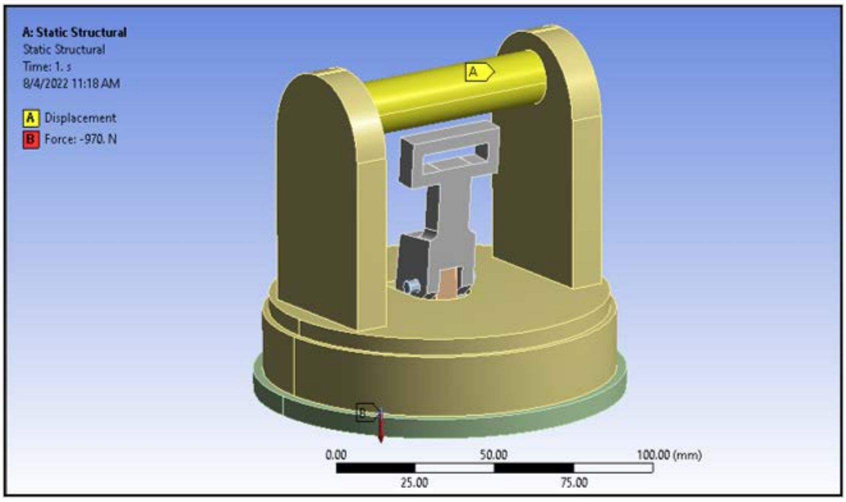

Figure 7. Loads and boundary conditions

2.2.4 Solution stage

Upon establishing the loads and boundaries, the solution phase was initiated. Matrices for various parts of the object were developed [19]. A collective, encompassing matrix was formulated through the combination of smaller matrices, yielding insights into the potential bending and stretching capacities of the object. Subsequent processes entailed matrix inversions and multiplications, with nodal computations inclusive of deformations and stress assessments. Final results were extrapolated across the entirety of the object's sections.

3 Results

3.1 FEA Analysis of Natural Rubber (NR)

In the presented scenario, structural steel constitutes the body, whilst the cap is fabricated from natural rubber. NBR and polyurethane emerge as materials of interest, selected in light of a myriad of factors, including their intrinsic material properties, durability, cost-effectiveness, availability, compatibility with manufacturing processes, and demonstrated efficacy in analogous applications. These attributes collectively render them potent candidates for enhancing the performance of suction cup handling systems. A comprehensive assessment involves an analysis of ES, deformation, and shear stresses in both the cap and the body.

The depiction of ES distribution within the NR cap is provided in Figure 8, whereas Figure 9 illustrates the total deformation generated. A grid independence test was conducted on the suction cup, with detailed outcomes elucidated in Table 1.

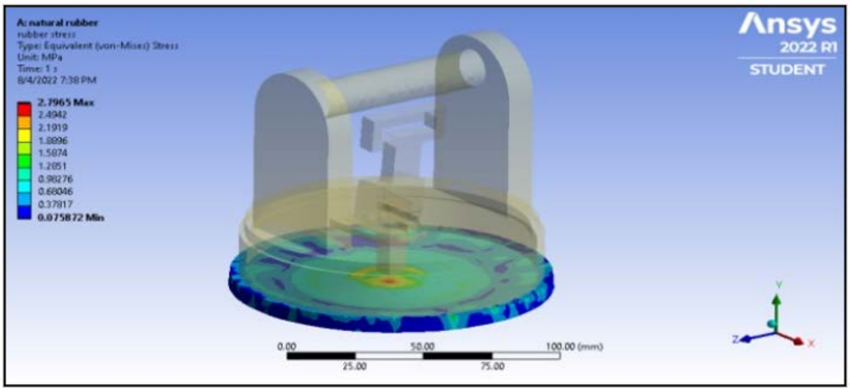

Figure 8. ES distribution on suction cup (NR cap)

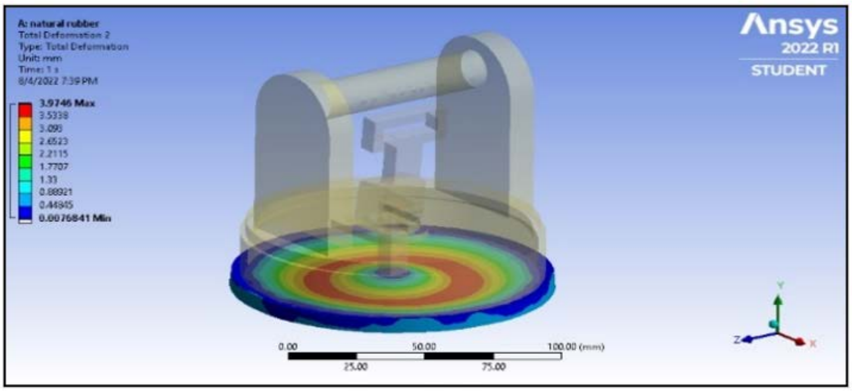

Figure 9. Total deformation generated on suction cup (NR cap)

Table 1. Grid independence test details

Number of Elements	ES (MPa)
11282	2.6785
11584	2.7159
11997	2.7847
12155	2.7965

The pinnacle of ES, arriving at 2.7965 MPa, is centrally located at the cap, visualised in the designated red area. Stress levels in alternate regions approximate 0.982 MPa, denoted by the light blue zone. Upon scrutiny of the total deformation graph, maximal deformation, quantifying at 3.9746 mm, is discernible in the concentric red area.

A depiction of the shear stress (SS) plot for the body is encapsulated in Figure 10. Corner points become apparent as locations of peak SS, as evidenced by the red zone in the SS figure. This investigation illuminated a maximal SS of 7.128 MPa.

Subsequent analysis of the ES distribution for the body, as demonstrated in Figure 11, unveils that the predominance of areas endure an ES of 7.601 MPa. However, an elevated ES of 12.618 MPa is witnessed in the corner region.

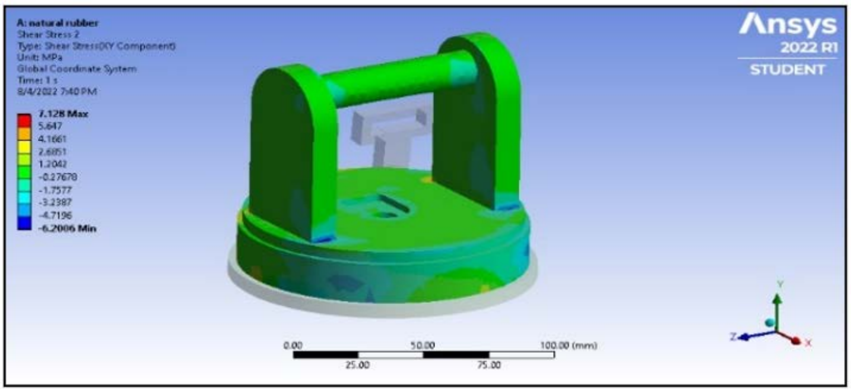

Figure 10. SS generated on body (NR cap)

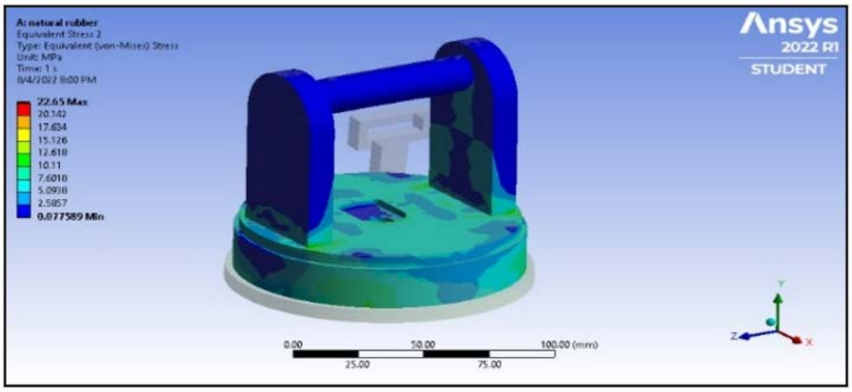

Figure 11. ES generated on body (NR cap)

3.2 FEA Analysis of NBR

Figure 12 delineates the distribution of ES within the NBR cap. A maximal ES, measuring 2.7583 MPa, is observed at the centre of the cap, represented by a red-hued area. Conversely, surrounding regions exhibit a stress of approximately 0.967 MPa, depicted by the light blue zone.

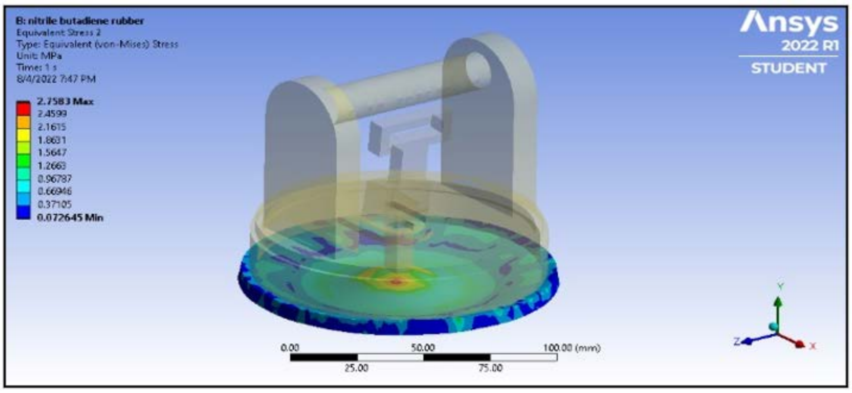

Figure 12. ES distribution on suction cup (NBR cap)

Subsequent analysis of the total deformation graph reveals a pinnacle of deformation, quantifying 8.1707 mm, within the concentric red zone, as exhibited in Figure 13.

SS examination for the body is conducted and encapsulated in Figure 14. The diagram indicates that the apogee of SS is discerned at the corner points, designated by the red zone, with the investigation elucidating a maximal SS value of 6.988 MPa.

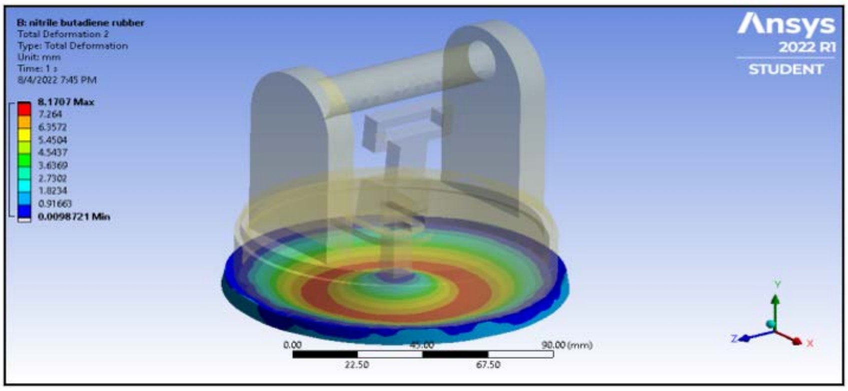

Figure 13. Total deformation generated on suction cup (NBR cap)

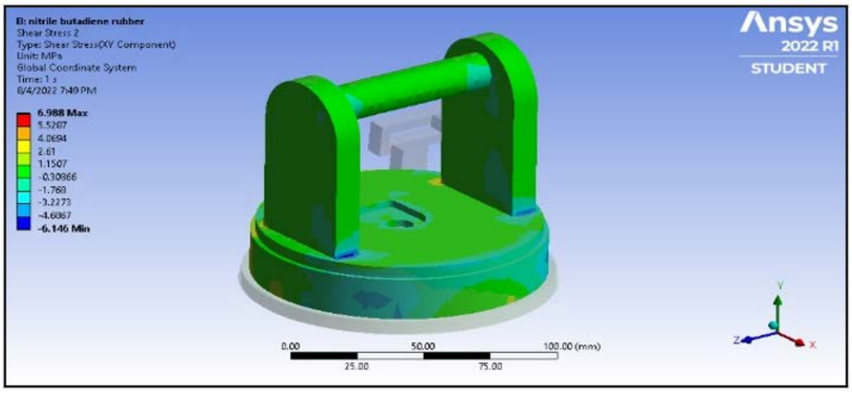

Figure 14. SS generated on body (NBR cap)

ES analysis for the body, depicted in Figure 15, unveils that regions proximate to the edges manifest an ES of 12.451 MPa, whereas an ES of 5.027 MPa is noted in the outer region. The induced ES on the suction cup body remains well beneath the yield strength of the material, thereby affirming safety per the Von-Mises Criteria [20].

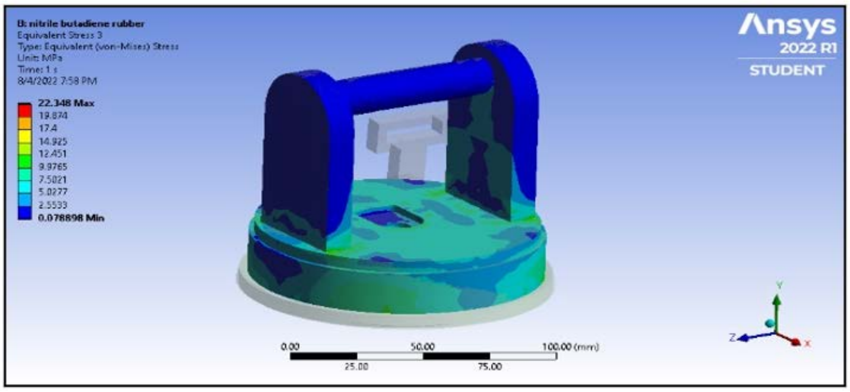

Figure 15. ES generated on body (NBR cap)

3.3 FEA Analysis of PR

Polyurethane has garnered recognition for its superior resilience compared to plastic, rubber, and steel, particularly when subjected to a myriad of strenuous environmental conditions, encompassing abrasion, heat, solvents, oil, and acid. Figure 16 elucidates the ES distribution within the PR cap. The acme of ES is situated at the center of the cap, amounting to 2.4498 MPa, as demarcated by the red region. Ancillary areas exhibit a stress of approximately 1.3942 MPa, delineated by the light blue zone.

An examination of the comprehensive deformation plot, showcased in Figure 17, reveals the zenith of deformation, quantifying 3.3551 mm, within the concentric area highlighted in red.

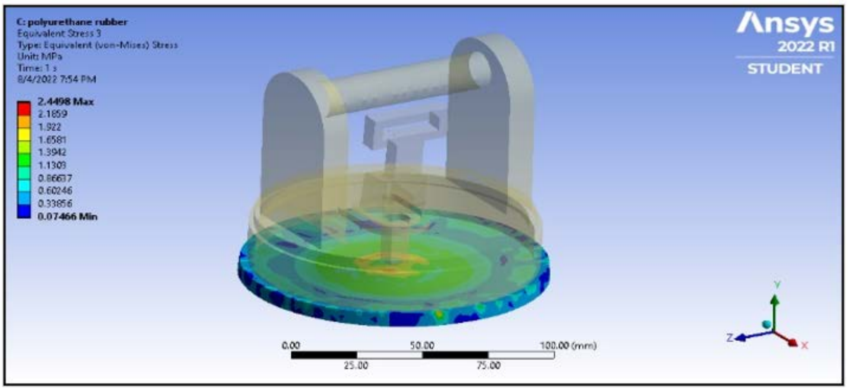

Figure 16. ES dissemination on suction cup (PR cap)

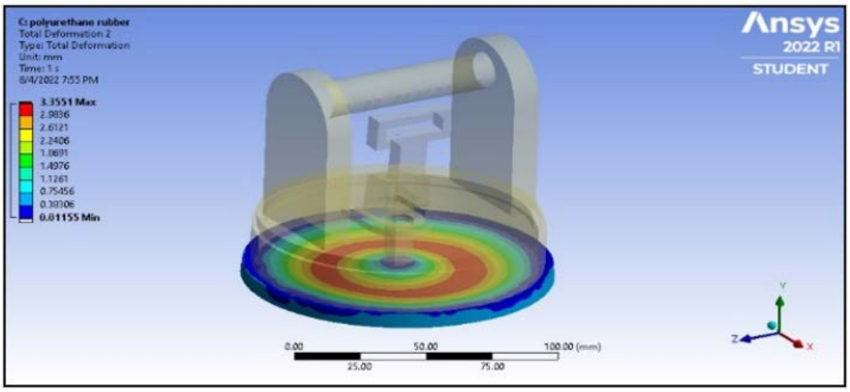

Figure 17. Comprehensive deformation manifested on suction cup (PR cap)

An assessment of the SS distribution for the body, illustrated in Figure 18, indicates that the pinnacle of SS is localized at the corner points, highlighted in red, resulting in a maximum SS value of 7.0711 MPa.

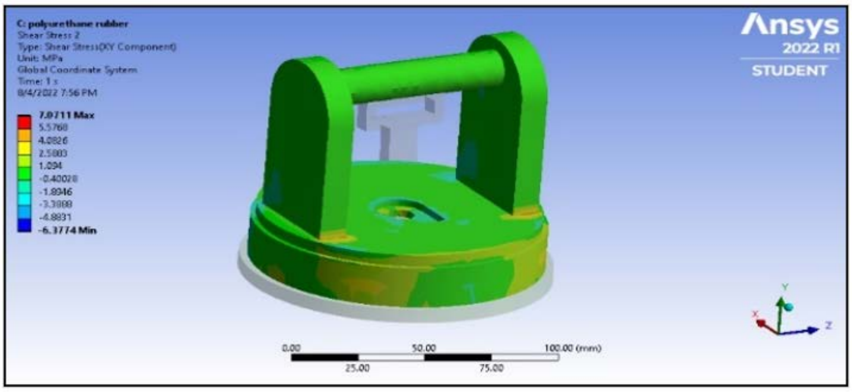

Figure 18. SS distribution on body (PR cap)

The exploration of ES for the body, depicted in Figure 19, unveils that the vicinities adjoining the edges are subject to an ES of 12.931 MPa, while the outer area experiences an ES of 5.219 MPa.

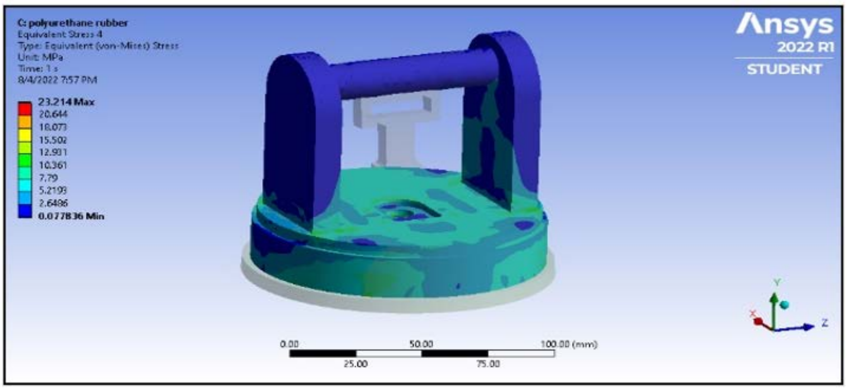

Figure 19. ES distribution on body (PR cap)

3.4 FEA of a Lightweight Suction Cup: Carbon Composite & Polyurethane

An endeavour to attenuate the weight of the suction cup body invoked the utilisation of CCM. FEA was implemented to scrutinise the stress and shear forces exerted upon the suction cup body. As visualised in Figure 20, the apogee of stress was discerned at the corners, illuminated in red, with a formidable stress measurement of 26.146 MPa. Conversely, stress in disparate regions hovered around 20.33 MPa.

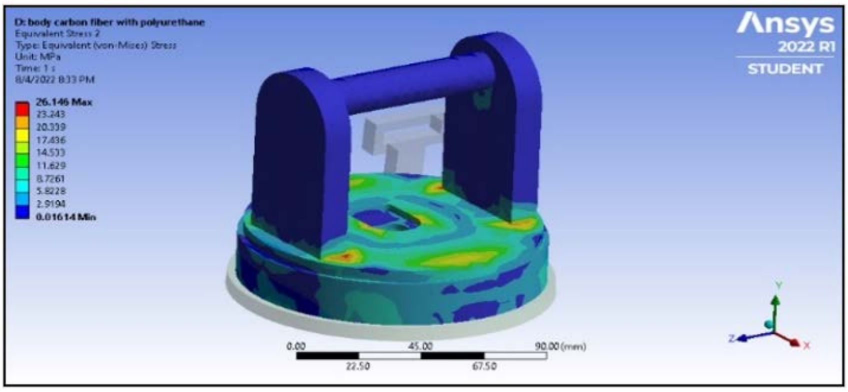

Figure 20. Manifestation of ES on body (PR cap)

Further, an analysis of the SS distribution, depicted in Figure 21, unveils a nearly uniform pattern along the vertical structural elements, accentuated by the green-highlighted area. Pertinent attention was afforded to the SS in the vicinities of the rounded corner area.

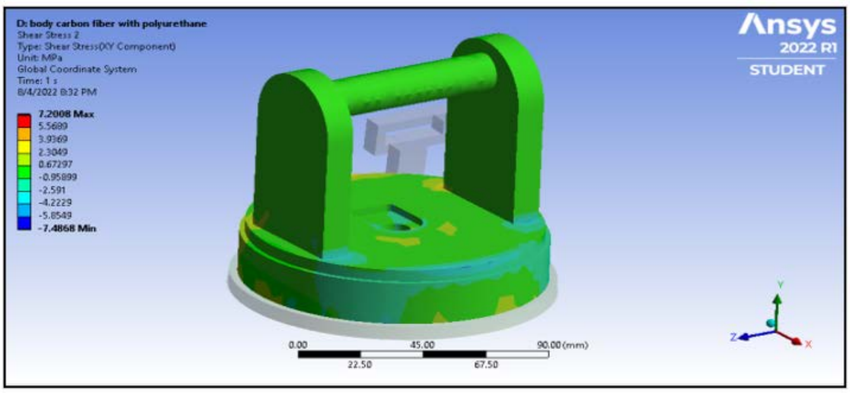

Figure 21. SS distribution on body (PR cap)

3.5 Correlation Between Suction Cup Diameter and Resultant Stresses

A meticulous exploration regarding the influence of the suction cup's diameter on induced stresses is undertaken in this section, wherein distinct diameters, specifically 95 mm and 141 mm, are evaluated under defined loading conditions.

3.5.1 Stress analysis for 95 mm diameter cup

As portrayed in Figure 22, the apex of SS is identified at the centre of the cup. An ES of 2.1129 MPa is computed, whereas a SS of 1.647 MPa is documented in the peripheral regions.

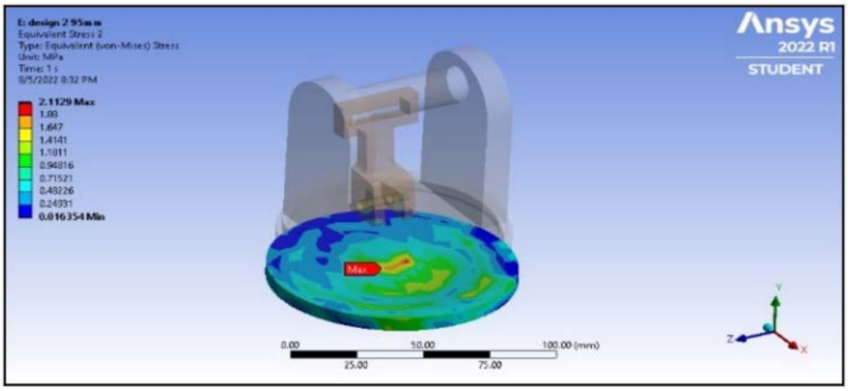

Figure 22. Distribution of SS across the cup

Figure 23 discloses the deformation graph, revealing a pinnacle of deformation, quantified as 3.917 mm, at the central area, indicated by the red zone. Conversely, a nominal deformation, specifically 0.00122 mm, is discerned in the corner area.

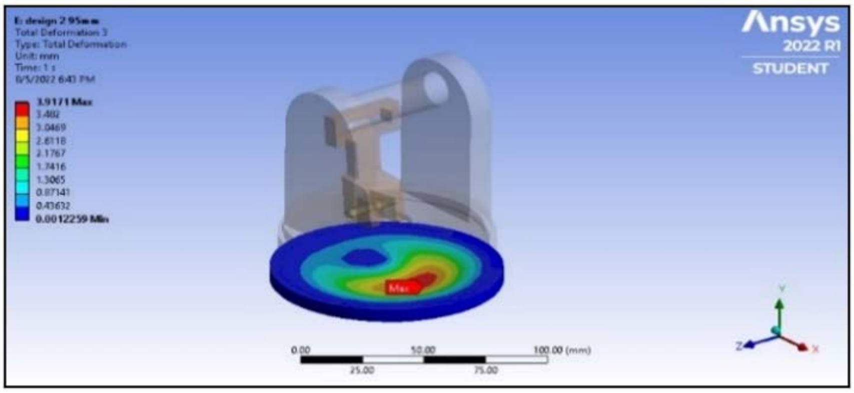

Figure 23. Comprehensive deformation representation

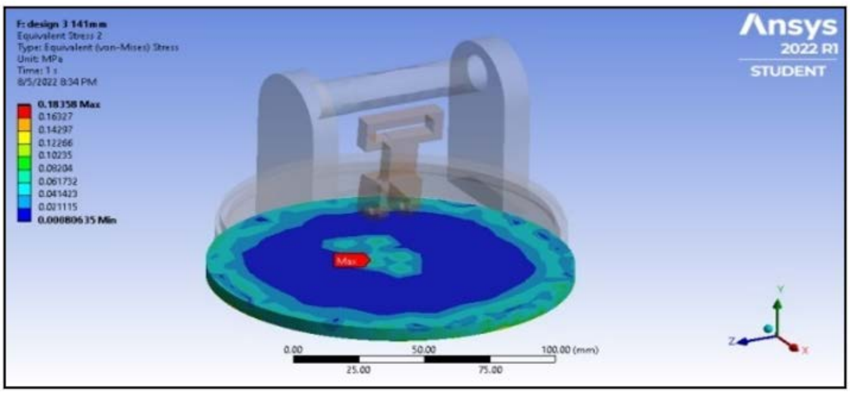

Figure 24. Graphical representation of ES

3.5.2 Stress analysis for 141 mm diameter cup

Within Figure 24, the centre is illuminated as the locus of the paramount SS. The ES and the SS in the outer regions are quantified to be 0.183 MPa and 0.1023 MPa, respectively.

Figure 25 elucidates the deformation across the cup, wherein the zenith of displacement, amounting to 0.124 mm, is discernible at the centre, as signalled by the red delineation. The peripheral region, however, experiences a mitigated displacement, registering at 0.014 mm.

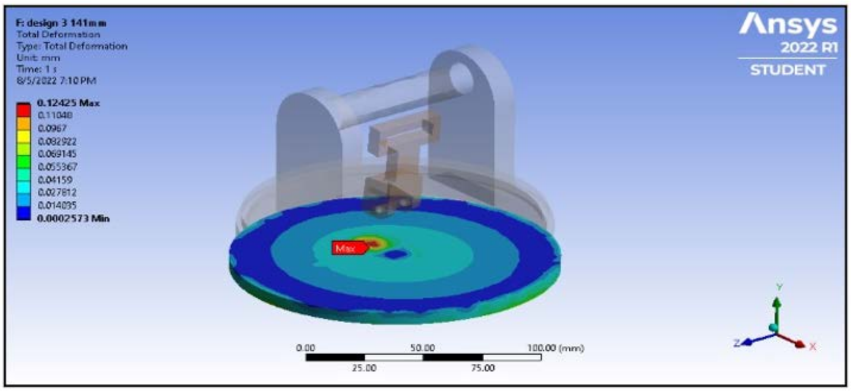

Figure 25. Deformation spectrum across the cup

3.6 Comparative Evaluation of Rubber Material and Constructional Variants

A comprehensive analysis, encompassing various rubber materials, namely NR, NBR, and PR, has been undertaken. The ensuing ES and deformation values are succinctly encapsulated in Table 2.

Table 2. Consequential outputs pertaining to suction cup material

Substance	NR	NBR	PR
ES (MPa)	1.7965	2.7583	2.4498
Deformation (mm)	3.9746	8.1707	3.3551

Figure 26 delineates the comparative data of ES across diverse suction cup materials, wherein the nadir of ES is identified in natural rubber, while the zenith is ascribed to NBR.

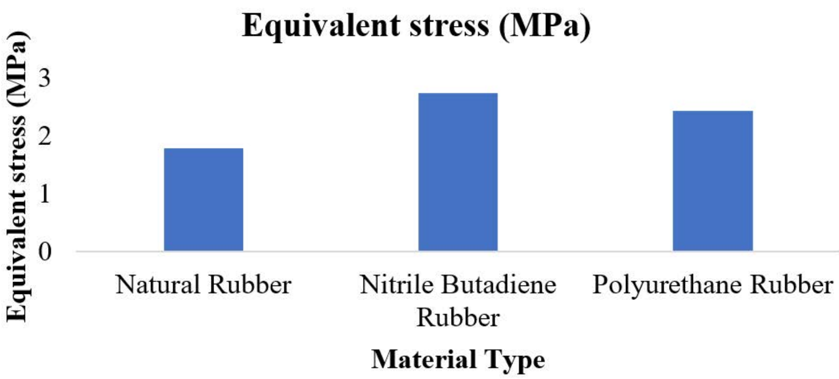

Figure 26. Comparative plot highlighting ES across materials

A meticulous comparison of deformation is rendered via Figure 27, with polyurethane rubber demonstrating the least deformation, gauged at 3.3551 mm. Subsequent to employing a CCM that is distinctly lighter than carbon steel, a focused analysis was executed on the suction cup body, with pertinent results enumerated in Table 3.

In Figure 28, a comparative chart elucidating the ES across different suction cup bodies is presented. A measure of 26.146 MPa is documented for the carbon composite body, whereas the carbon steel body manifests an ES of 23.214 MPa.

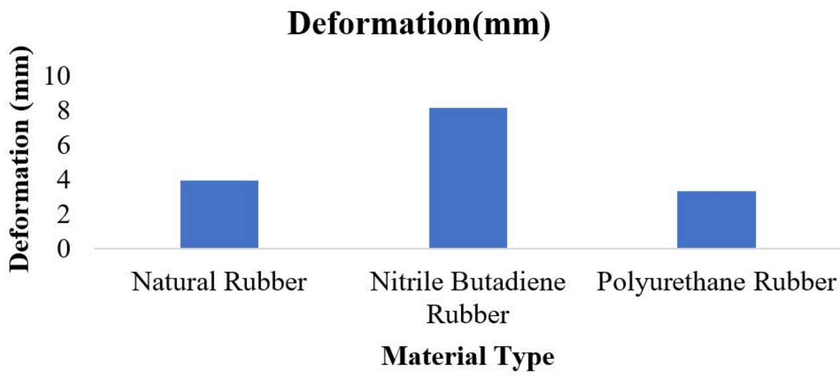

Figure 27. Comparative illustration of deformation across materials

Table 3. Outcomes pertaining to the suction cup body

Kind of Substance	Carbon Steel	Carbon Composite
ES (MPa)	23.214	26.146
SS (MPa)	7.0771	7.2008
Mass (Kg)	1.2032	0.292

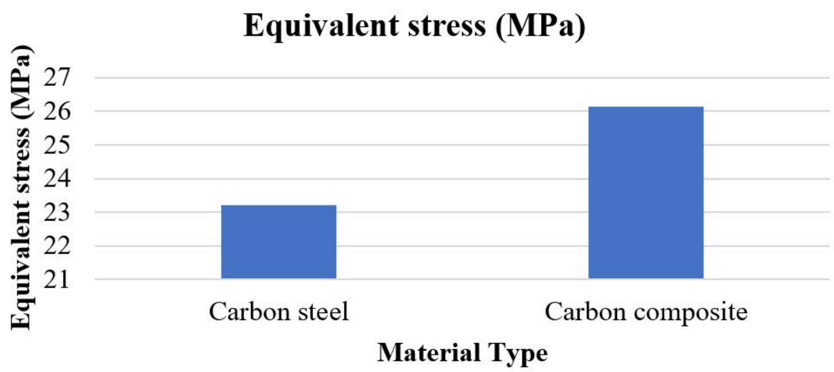

Figure 28. Comparative ES across suction cup bodies

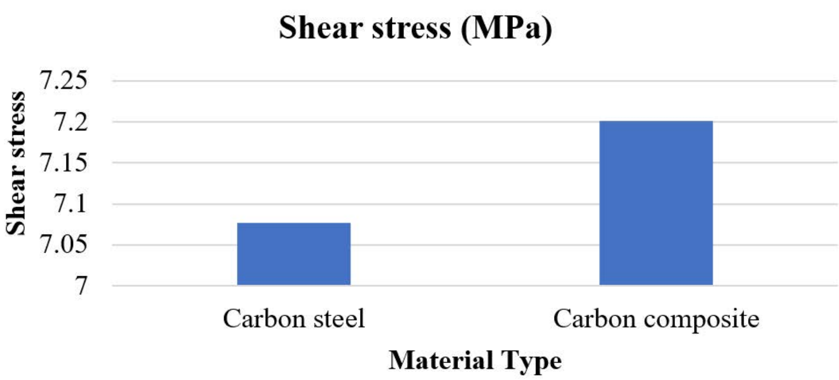

Figure 29. SS comparative analysis for suction cup bodies

Figure 29 unveils the SS comparative chart for the suction cup body, revealing a marginally higher SS for the carbon composite body (7.2008 MPa) relative to the carbon steel counterpart (7.0771 MPa).

A comparative analysis of mass for the suction cup bodies, exhibited in Figure 30, demonstrates a notably diminished mass in the instance of the carbon composite suction cup relative to the carbon steel variant.

Table 4 elucidates a comparative exploration of suction cup diameters.

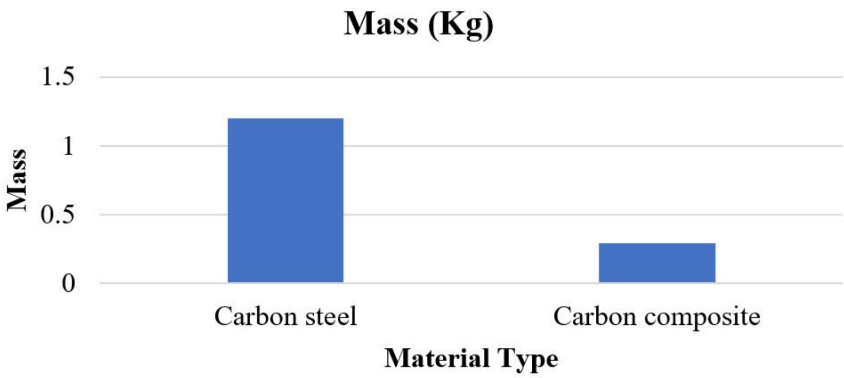

Figure 30. Comparative mass illustration for suction cup bodies

Table 4. Comparative analysis of suction cup diameters

Cup Diamater	95 mm	118 mm	141 mm
ES (MPa)	2.1129	2.7965	0.18358
Deformation (mm)	3.9171	3.9746	0.1242

A comparison plot, elucidating the ES across various suction cup diameters, was generated, as depicted in Figure 31. The analysis revealed that a suction cup with a diameter of 141 mm experienced the most minimal deformation, whereas the acme of ES was identified in the case of a suction cup with a diameter of 118 mm.

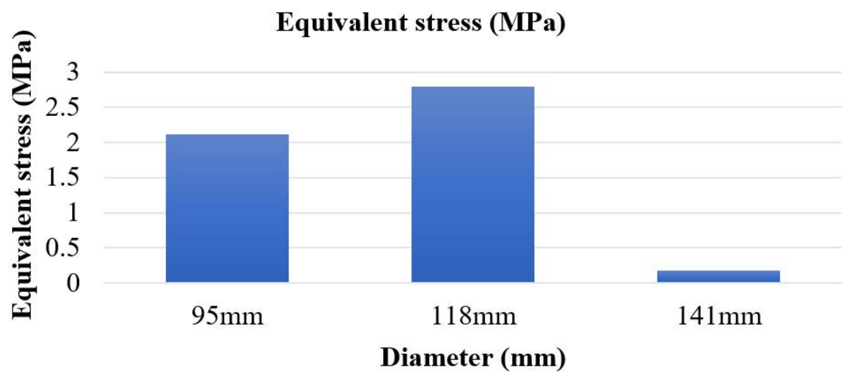

Figure 31. ES comparative chart across diameters

Further examination of the deformation comparison plot, presented in Figure 32, made it apparent that the scantiest deformation was manifested by a suction cup diameter of 141 mm, while the largest deformation was associated with a diameter of 118 mm.

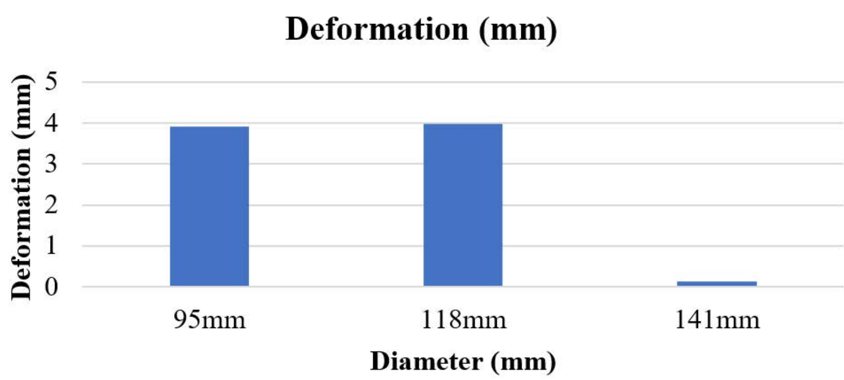

Figure 32. Deformation comparative chart across diameters

Consequently, the selection of a suction cup with a diameter of 141 mm appeared to be judicious, attributing to the reduced incidence of induced stresses and deformation. Ergo, it was established that, concerning the suction cup body, critical regions of elevated stresses were located proximate to the edges. The deformation encountered for polyurethane suction cups was ascertained to be 15.58% lower than that of NR suction cups. Furthermore, although the ES identified for polyurethane suction cups exceeded that of NR suction cups, it remained comfortably within the safe limit, not breaching the yield strength.

4 Conclusions

An exploration into the strength of suction cups was undertaken, employing FEM techniques. Utilisation of FEA tools availed a streamlined approach, both temporally and financially, for the evaluation of suction cups. The derivations from the FEA facilitated the identification of focal areas where stress and deformation presented notably elevated levels. The research penetrated into the effects imparted by variations in material types upon stress and deformation within the suction cup.

Acknowledgment of inherent limitations within the study is imperative. Initial limitations can be pinpointed to the simplifications and assumptions upon which the FEA simulations were reliant, essential for computational feasibility. Further, the study predominantly cast light upon a specified suction cup type and diameter range, thereby proffering valuable insights whilst possibly not encapsulating the exhaustive spectrum of suction cup variations employed across diverse industries. Static loading analyses were engaged, providing a wealth of informative data but neglecting the often-encountered dynamic forces within practical applications. The assumptions of idealised environmental conditions and the validation data from empirical, real-world measurements may introduce certain constraints.

The implications of these research findings permeate various industrial applications reliant upon suction cup technology, holding substantial promise for practical applicability. Potential avenues for impactful application of these insights into tangible enhancements in suction cup design and performance across diverse sectors are delineated below:

(1) Material Selection Enhancement: The research engaged in a rigorous evaluation of the performance of two pivotal materials, NBR and polyurethane, within suction cup applications, yielding valuable guidance for industry material selection and ensuring alignment with the explicit demands of their respective applications.

(2) Optimisation of Design Parameters: Identification of optimal design parameters, inclusive of suction cup diameter and structural characteristics, was achieved. Such information paves the way for industries to meticulously tailor suction cup designs to meet their explicit needs, such as leveraging a larger 141 mm diameter to mitigate stress, thereby proving beneficial in industries requiring heightened load-bearing capacity.

(3) Durability Augmentation: Discerning the patterns of stress distribution, deformation, and elastic strain facilitates the formulation of measures to enhance suction cup durability. Such measures could encompass the design of reinforcements within critical stress areas and selecting materials that resist wear from repeated utilisation, thereby curtailing maintenance expenditures and operational downtimes.

(4) Safety Augmentation: Suction cups, pivotal in the handling of fragile or valuable items, benefit from the predictive capabilities related to stress concentrations and deformation, contributing to the enhancement of operational safety.

(5) Environmental Impact Mitigation: In-depth exploration into material suitability, inclusive of sustainability factors, allows industries to implement eco-conscious decisions in material selection for suction cups, thereby reducing their environmental impact.

(6) Application Versatility: The adaptable nature of the research findings enables various sectors to optimise suction cup performance, tailoring the technology to meet distinct industry requirements.

The meticulous refinement and strategic reorganisation of the content aimed to align with the stringent language and structural prerequisites of premier academic journals, ensuring a coherent, logically articulated, and professionally resonant conclusion section. Enhanced scrutiny by a subject-matter expert may further refine technical and professional accuracy, ensuring the utmost fidelity to the research domain's standards and nuances. Further feedback is welcomed to assure the enhanced content succinctly aligns with all requisites and expectations.

4.1 Evaluation and Project Management

In the investigation conducted, a meticulous exploration into the variances in diameters and materials of suction cups was undertaken, revealing detailed findings as delineated:

- The apex of stress was identified to be centrally located within the suction cup, demarcating critical high-stress zones.
- Stress concentration within the suction cup body was observably prominent near the edges.
- Polyurethane suction cups were found to exhibit a deformation 15.58% lower compared to those of natural rubber.

• Whilst the ES in polyurethane cups surpassed that in natural rubber, it judiciously remained within a safe operating range, not breaching the yield strength.

• The ES and deformation parameters for NBR were determined to exceed those of NR but steadfastly remained within the designated yield strength.

• A significant reduction in the weight of the suction cup body was attained through the adoption of CCM. In comparison to a carbon steel body weighing 1.2032 kg, the carbon composite body exhibited a substantial reduction, weighing in at 0.292 kg.

• Equivalent and SS values in the carbon composite body, although surpassing those of carbon steel, judiciously remained within established safe limits.

• Amongst the various suction cup diameters scrutinised, those of 141 mm in diameter manifested minimal deformation, whereas their 118 mm counterparts demonstrated the maximal deformation.

• Correspondingly, suction cups of 141 mm in diameter were subjected to the lowest ES, while those of 118 mm in diameter were subjected to the highest.

• Optimal suction cup design was articulated as entailing a diameter of 141 mm, fabricated from polyurethane rubber, as a means to mitigate deformation.

• CCM was validated as a superior design element for suction cup bodies, delivering an enhanced strength-to-weight ratio when juxtaposed with its carbon steel counterparts.

These detailed findings, meticulously derived from the conducted exploration, not only facilitate a profound understanding of the nuanced performance characteristics of various suction cup materials and dimensions but also proffer insightful directives for future research and practical applications within this domain. Moreover, through a judicious amalgamation of ES, deformation, and strength-to-weight ratio findings, these insights harbour the potential to significantly influence future suction cup design paradigms, encompassing both material selection and dimensional considerations.

Refinement of these critical insights, guided by further investigations and empirical validations, could serve to fortify the foundational understanding and practical applicability of these findings across diverse industrial domains, thereby engendering enhancements in operational efficiency, safety, and product longevity in applications reliant on optimised suction cup technology.

4.2 Propagation into Novel and Inventive Application Domains

The conduction of this research posits a persuasive endorsement for the utilisation of polyurethane as a material of choice for suction cups. Demonstrations via FEA results elucidate the robustness of polyurethane under specified loads, thereby underpinning its appropriateness for applications of suction cups. Noteworthy is the exhibition of polyurethane's enhanced resistance to various environmental factors such as heat, abrasive wear, and an array of chemicals, including solvents, oils, and acids. Enhanced design and performance of suction cups across assorted industries have been illuminated, affording the following benefits:

• High Load Capacity: Polyurethane, capable of managing relatively hefty loads and providing commendable load-bearing capacity, has been identified. This revelation positions polyurethane suction cups as particularly apt for heavy-duty applications.

• Operational Temperature Range: Suction cups, when manufactured from polyurethane rubber, can efficaciously operate over a wider temperature range in contrast to NBR, embracing both extremities of the temperature spectrum.

• Minimised Residue: A notable low likelihood of mark or residue deposition on manipulated objects by polyurethane underscores its suitability in applications where maintaining surface integrity is paramount.

• Ultraviolet (UV) Resistance: The offering of augmented resistance to UV radiation by Polyurethane suction cups establishes them as pertinent for applications situated outdoors or in UV-exposed environments.

These innovations in material application, driven by the foundational insights derived from the research undertaken, propel the utility of suction cups into new spheres of application, subsequently facilitating improvements across a multitude of industries. It becomes implicit that these technological advancements, informed by empirical evidence, forge pathways for innovative implementations within, but not restricted to, manufacturing, logistics, and technology sectors.

The challenge moving forward involves the incorporation of these findings into practical applications, thus ensuring theoretical insights translate effectively into tangible, operational advancements. The meticulously extracted conclusions from this research may serve as a platform for future studies, instigating further exploration into innovative materials and designs, and propelling the body of knowledge and practical applications of suction cup technology into novel and expansive horizons.

4.3 Prospects for Subsequent Research

Comprehensive inquiries into suction cup management systems warrant an exhaustive exploration under a spectrum of thermal conditions and various surface topographies. Crucial are experimental tests involving polyurethane suction cups, especially on surfaces characterised by their irregularity and oleaginous nature. Moreover, the microstructural properties of suction cups within the aforementioned conditions merit detailed investigation.

A potential framework for ensuing research into suction cup technology could thus be delineated:

• Examination of Thermal and Surface Variances: An exhaustive analysis under an array of thermal scenarios and disparate surface conditions, which navigates through the intricacies of interacting variables, is to be undertaken.

• Experimental Undertakings on Polyurethane Suction Cups: Rigorous experimental tests, especially those concerning polyurethane suction cups on surfaces that are both irregular and lubricated, are to be prioritised.

• Microstructural Scrutiny: A meticulous analysis of the microstructure of suction cups, particularly within variable thermal and surface conditions, is requisite.

Further avenues for exploration may pivot towards investigating additional materials and configurations of suction cups to delineate their operational capacities and limitations under distinct environmental and load conditions. The proliferation of such studies has the potential to unveil new materials and design synergies, consequently expanding the horizon of applicative domains and enhancing performance metrics of suction cups across varied industries.

Additionally, computational models and simulations could be developed and fine-tuned, encapsulating real-world conditions to further validate and optimise experimental findings, thereby fortifying the empirical framework established in this research.

Emphasising the broader impact, insights procured from subsequent research could propel the current technological thresholds into innovative paradigms, thereby enriching the tapestry of knowledge and applications in the realm of suction cup technology. This, in turn, provides a solid foundation for augmenting technological efficiencies, fostering innovation, and sculpting the trajectory of future research endeavours.

Data Availability

Not applicable.

Conflicts of Interest

The author declares no conflict of interest.

References

[1] The Britannica Dictionary, "Suction cup," 2023. https://www.britannica.com/dictionary/suction-cup

[2] Professional Mariner Staff, "First inland vacuum-based mooring system installed on St. Lawrence Seaway locks," 2015. https://professionalmariner.com/first-inland-vacuum-based-mooring-system-installed-on-st-lawrence-seaway-locks/

[3] Z. Max, "Suction cups for attaching purposes; Equivalent means using adhesive," 1936. https://patents.google.com/patent/US2055397A/en

[4] The Suction Cup Museum, "Suction cup history," 2022. https://web.archive.org/web/20060424182733/http://www.suctioncupmuseum.com/html/history.html

[5] BBC, "Man climbs skyscraper with suction cups," 2010. https://www.bbc.com/news/av/world-us-canada-11210846

[6] T. McCulloch and D. Herath, "Towards a universal gripper-on the use of suction in the context of the Amazon robotic challenge," in *Australasian Conference on Robotics and Automation, Brisbane, Australia*, 2016, pp. 153–160.

[7] S. Kawasaki and K. Kikuchi, "Development of a small legged wall climbing robot with passive suction cups," 2014. https://api.semanticscholar.org/CorpusID:1123043

[8] N. Correll, K. E. Bekris, D. Berenson, O. Brock, A. Causo, K. Hauser, K. Okada, A. Rodriguez, J. M. Romano, and P. R. Wurman, "Analysis and observations from the first Amazon picking challenge," *IEEE Trans. Autom. Sci. Eng.*, vol. 15, no. 1, pp. 172–188, 2018. https://doi.org/10.1109/tase.2016.2600527

[9] J. Doshi Sachindra, "Design of vacuum operated wall climbing robot," *Int. J. Adv. Eng. Res. Dev.*, vol. 4, no. 8, 2017.

[10] D. Ge, T. Matsuno, Y. Sun, C. Ren, Y. Tang, and S. Ma, "Quantitative study on the attachment and detachment of a passive suction cup," *Vacuum*, vol. 116, pp. 13–20, 2015. https://doi.org/10.1016/j.vacuum.2015.02.013

[11] J. Schmalz, L. Kiefer, and F. Behncke, "Analysis of the system handling using methods of structural complexity management," *Appl. Mech. Mater.*, vol. 794, pp. 27–34, 2015. https://doi.org/10.4028/www.scientific.net/amm.794.27

[12] A. Tiwari and B. N. J. Persson, "Physics of suction cups," *Soft Matter*, vol. 15, no. 46, pp. 9482–9499, 2019. https://doi.org/10.1039/c9sm01679a

[13] V. Tinnemann, L. Hernández, S. C. L. Fischer, E. Arzt, R. Bennewitz, and R. Hensel, "In situ observation reveals local detachment mechanisms and suction effects in micropatterned adhesives," *Adv. Funct. Mater.*, vol. 29, no. 14, p. 1807713, 2019. https://doi.org/10.1002/adfm.201807713

[14] F. Gabriel, M. Fahning, J. Meiners, F. Dietrich, and K. Dröder, "Modeling of vacuum grippers for the design of energy efficient vacuum-based handling processes," *Prod. Eng.*, vol. 14, no. 5-6, pp. 545–554, 2020. https://doi.org/10.1007/s11740-020-00990-9

[15] G. Du, K. Wang, S. Lian, and K. Zhao, "Vision-based robotic grasping from object localization, object pose estimation to grasp estimation for parallel grippers: A review," *Artif. Intell. Rev.*, vol. 54, no. 3, pp. 1677–1734, 2020. https://doi.org/10.1007/s10462-020-09888-5

[16] A. Agarwal and L. Mthembu, "Investigation of dynamic factors in different sections of HVC by static and free vibration modal analysis," *Annales de Chimie - Science des Matériaux*, vol. 46, no. 2, pp. 75–84, 2022. https://doi.org/10.18280/acsm.460203

[17] A. Agarwal, "Modelling & numerical investigation of the effectiveness of plate heat exchanger for cooling engine oil using ANSYS CFX," *Int. J. Heat Technol.*, vol. 39, no. 2, pp. 653–658, 2021. https://doi.org/10.18280/ijht.390237

[18] A. Agarwal and L. Mthembu, "CFD analysis of conical diffuser under swirl flow inlet conditions using turbulence models," *Mater. Today Proc.*, vol. 27, pp. 1350–1355, 2020. https://doi.org/10.1016/j.matpr.2020.02.621

[19] M. T. Letsatsi and A. Agarwal, "Optical analysis of T-shaped stiffened plate under compressive loading using central composite design scheme," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 992, no. 1, p. 012001, 2020. https://doi.org/10.1088/1757-899x/992/1/012001

[20] E-Funda, "Maximum shear stress criterion," 2023. https://www.efunda.com/formulae/solid_mechanics/failure_criteria/failure_criteria_ductile.cfm#MaxShear