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Improving Customer Satisfaction and Packaging Quality in Sunscreen Products: A Case Study on Failure Analysis and Design Improvement

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ABSTRACT

Sunscreen packaging plays a crucial role in enhancing customer satisfaction and shaping brand perception, both of which significantly influence profitability in the skincare industry. This study was initiated in response to repeated customer complaints about leakage and breakage in a sunscreen product from a beauty company, prompting an investigation into the causes of packaging failure. Experimental testing using a universal compression machine revealed that the cap, though labelled as aluminium, was actually made from brittle plastic, highlighting serious issues in material quality and transparency. Simulation analysis confirmed structural weaknesses in the cap design, emphasizing the need for improvements in both materials and engineering. These findings also uncovered broader concerns, such as poor material traceability and weak oversight in procurement and production processes. To address these issues, the study recommends sourcing verified materials, redesigning the cap for improved durability, and adopting a more customer-focused approach to packaging. This case illustrates the vital role of packaging integrity in maintaining brand trust, improving customer retention, and ensuring operational effectiveness in a highly competitive market.

1. Introduction

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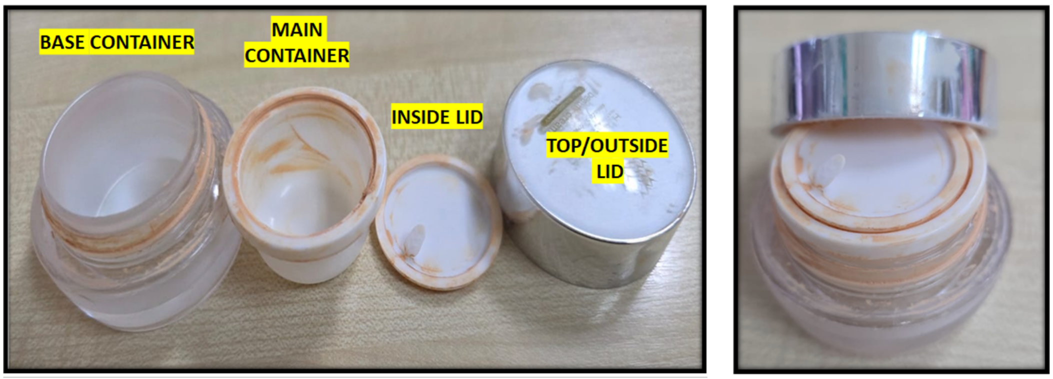
The global beauty industry has been expanding rapidly, with the cosmetics market valued at approximately USD 262.21 billion in 2022 and projected to grow at a compound annual growth rate of 4.2 percent from 2023 to 2030 [1]. Packaging plays a critical role in shaping customer satisfaction and brand perception in this sector. Companies often collaborate with specialized packaging firms to create tailored and visually appealing product designs, integrating branding and marketing strategies. However, these efforts sometimes overlook the practical robustness and durability of packaging during customer use. A notable case involving a sunscreen product from a skincare company (name withheld for confidentiality) highlights these challenges. Customers reported frequent issues with leakage and breakage, prompting the company to seek assistance in identifying and addressing the underlying problems.

Sunscreen packaging typically employs a variety of materials such as acrylic, aluminum, plastic, cardboard tubes, and post-consumer recycled (PCR) materials, often chosen with sustainability in mind to align with the United Nations Sustainable Development Goals (SDGs). While complaints in the skincare industry often concern product ingredients or pricing, this particular investigation focuses on structural flaws in packaging. The company lacked clarity about the specific materials used, though the product appeared to be housed in a small glass bottle with an aluminum cap. Upon closer inspection, the design was found deficient in material quality, indicating a need for improvement and more sustainable packaging solutions. This case study seeks to evaluate the reported failures, determine their causes, and propose design and material changes to prevent future occurrences.

1.1 Customer Reported Issues

The sunscreen packaging consists of four main components which are the top/outside lid, the inside lid, the main container, and the base container. The main container is where the sunscreen paste or fluid is stored. Figure 1 illustrates these components and shows the complete packaging structure for the sunscreen. Customers expressed dissatisfaction with the poor quality and packaging design of a skincare sunscreen product. Common complaints included product breakage, leakage, difficulty opening the container, and a general lack of durability. Each complaint was supported by photographs showing the damage, along with detailed explanations provided by the customers.



(a) (b)

Fig. 1. Sunscreen packaging (a) Four main components (b) Complete sunscreen assembly

1.1.1 Case one

The first case, a customer reported, “I placed the sunscreen product in my bag, but because the lid was loose, the fluid leaked out.” Figure 2 displays the resulting damage, with sunscreen visibly spilled inside the customer's bag.

Report on Customer Case One

Illustration of case

Sunscreen Leakage Incident Reported by Customer

A customer reported that sunscreen had spilled from the bottle, resulting in damage to her bag. According to her, the cap appeared slightly loose but showed no visible defects or damage prior to placing the product in her bag. However, when she attempted to use the sunscreen, she discovered that the cap was missing and the contents had leaked inside her bag. The customer expressed significant dissatisfaction with the incident not only did the leakage stain and dirty her personal belongings, but it also led to a considerable loss of the product. She mentioned that the sunscreen, which would typically last for a month, may now only last for about two weeks due to the spillage.

Fig. 2. Case one: Customer complaint regarding bag stained by leaking sunscreen packaging

1.1.2 Case two

Another customer, in the second complaint, described the lid as being very thin and easily breakable. As shown in Figure 3, half of the lid had broken off and was missing. Due to this damage, the customer is no longer able to securely close or tighten the sunscreen bottle.

Report on Customer Case Two

Illustration of case

Broken Cap/Lid Incident Reported by Customer

A customer reported that the cap of the sunscreen bottle was broken. She described the lid as very thin and fragile, stating that it broke easily. When she attempted to apply the sunscreen, she noticed that half of the cap had broken off and was missing. The customer emphasized that the product was newly purchased, and expressed her disappointment with the packaging quality due to this issue.

Fig. 3. Case two: Customer provides evidence of thin and broken lid

1.1.3 Case three

In a third complaint, another customer reported that the sunscreen lid begins to crack and eventually breaks when subjected to even a small amount of force, such as a minor impact. Figure 4 provides visual evidence showing the broken part of the lid.

Report on Customer Case Three

<u>Illustration of case</u>

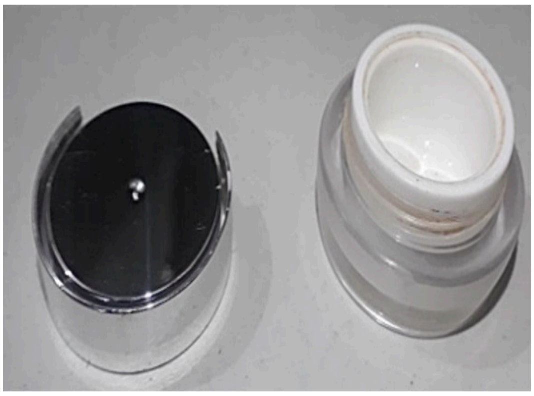
Broken Lid Due to Low Impact Resistance

A customer reported that the sunscreen lid broke into several small pieces after only a minor impact. She noted that the lid should normally withstand such small hits, but in this case, it cracked and shattered unexpectedly. This incident left the customer dissatisfied with the packaging quality, as it requires unusually careful handling to avoid damage.

Fig. 4. Case three: Evidence of lid damage from minor impact

1.1.3 Case four

The fourth type of complaint concerns the lack of sustainability in the current sunscreen packaging as shown in Figure 5. The customer expressed that adopting more environmentally friendly and durable packaging would be a valuable improvement. The photo below highlights the weaknesses of the existing packaging, as pointed out by the customer.



Report on Customer Case Four

<u>Illustration of case</u>

Cracking Lid Highlights Packaging Flaw and Sustainability Concerns

According to the customer, the cap shown in the attached photo is thin and easily breakable, clearly demonstrating a flaw in the current packaging design. Beyond the inconvenience it causes, this issue raises concerns about the overall sustainability of the product. The customer expressed a preference for sunscreen packaging made from materials that are both durable and environmentally friendly.

Fig. 5. Case four: Cracking lid raises concern over packaging durability and sustainability

All conditions of the sunscreen packaging, both before and after breakage, are shown in Figure 6. Due to strong customer complaints regarding the lid's fragility, the beauty brand is now seeking to improve the quality of its packaging design. Additionally, incorporating sustainable packaging materials is seen as a positive step toward aligning the product with the company’s Sustainable Development Goals (SDGs) and enhancing future design improvements.

(a) (b)

Fig. 6. Sunscreen product shown in (a) new and intact condition, and (b) various severe breakage conditions, particularly highlighting damage to the cap of the bottle

Based on the observed complaints, this case study aims to evaluate the key factors influencing the sunscreen packaging design, referencing customer feedback received by the beauty company. While the sunscreen's internal formulation has been well-received and praised by customers, the packaging has drawn significant dissatisfaction due to issues with durability and leakage. Sunscreen is an essential product, playing a crucial role in protecting the skin from harmful ultraviolet (UV) rays. However, customer complaints have highlighted that the current packaging easily breaks or leaks, compromising product usability and reducing customer satisfaction. Poor packaging design not only leads to inconvenience and product waste but can also compromise the product's effectiveness. A user-friendly, easy-to-open design combined with sustainable packaging materials is necessary to meet modern consumer expectations. Sustainability in packaging helps reduce the depletion of natural resources and supports long-term environmental and commercial goals) [2].

Sunscreen packaging must meet strict requirements to ensure the integrity of the product. UV filters within sunscreens absorb incoming UV rays to protect the skin from sunburn and aging. However, if the packaging fails to protect these filters from UV exposure during storage, the product's effectiveness may degrade [3]. When selecting packaging materials, three critical properties must be considered: light transmittance, oxidation resistance, and temperature tolerance [4]. Studies show that many plastics reduce the transmission of UV-B and UV-C rays. For example, polymethyl methacrylate (acrylic glass) effectively absorbs UV radiation between 200–235 nm, while polyethylene terephthalate (PET) blocks UV rays between 200–310 nm [5]. High temperatures can also accelerate oxidation of the product. Infrared light heats the packaging, and the UV filters themselves generate heat while absorbing UV radiation. Using reflective surfaces on packaging can help reduce heat absorption and thus protect the product [4].

In this case, the company's bottom packaging already meets acceptable standards for UV protection, as it uses acrylic glass (Figure 1). However, the top cover, particularly the lid, has received repeated complaints for being thin, brittle, and prone to cracking or breaking under minor pressure. Several customers reported incidents where the cap broke, leaked inside bags, or shattered upon light impact. Another common complaint focused on the lack of sustainable packaging. These issues collectively indicate the need for immediate packaging design improvement. Sustainability is becoming a growing priority among consumers, cosmetic brands, and researchers alike [6]. Green and ecological packaging design not only fulfills sustainability goals but also allows for creative and attractive product presentation. Poor packaging can lead to product loss, difficulty in usage, reduced protection, and poor storage convenience. This study will evaluate various failure cases reported by customers, including cracked lids, leakage, and material fragility, using both experimental and simulation-based methods. The findings aim to guide improvements in packaging design, especially with regard to durability and sustainability. While the company's name is kept confidential to maintain its reputation, the goal is to develop actionable solutions to enhance both customer satisfaction and alignment with sustainability goals.

2. Methodology

Figure 7 illustrates the research flow, beginning with analyzing packaging failures based on customer complaints and evidence, which form the basis for data collection through failure analysis, processing analysis, and mechanical testing. Photographs of complaints were provided by the beauty company, alongside a meeting with the company owner to discuss the issues.

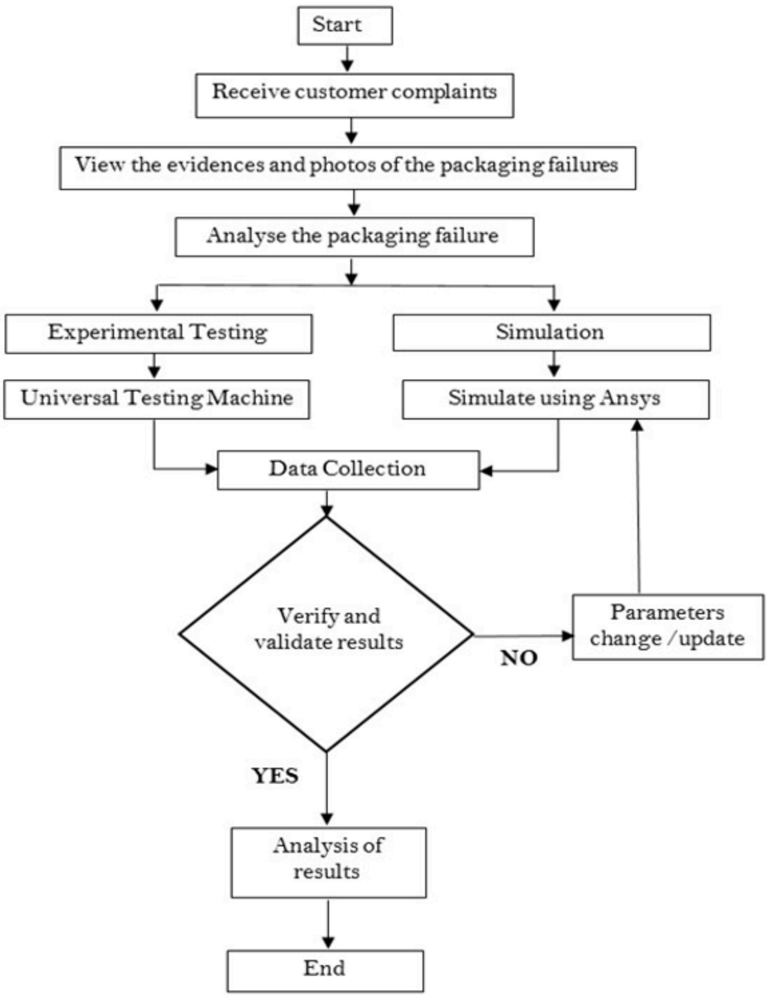


Fig. 7. The flow of research to sunscreen to determine its failures

After identifying the packaging failure problems, experimental testing was conducted using the Universal Testing Machine (Shimadzu) at Universiti Teknologi Malaysia, Kuala Lumpur, where compression tests on sunscreen lids were performed with a force of 18,000 N. In this experiment, the stress-strain graph will be obtained specifically utilizing the Shimadzu model for initial compression testing, as shown in Figure 8. The Universal Testing Machine is a versatile mechanical testing instrument used to evaluate the mechanical properties of various materials. It applies controlled forces and records the corresponding deformation or displacement to assess how a material behaves under different loading conditions.

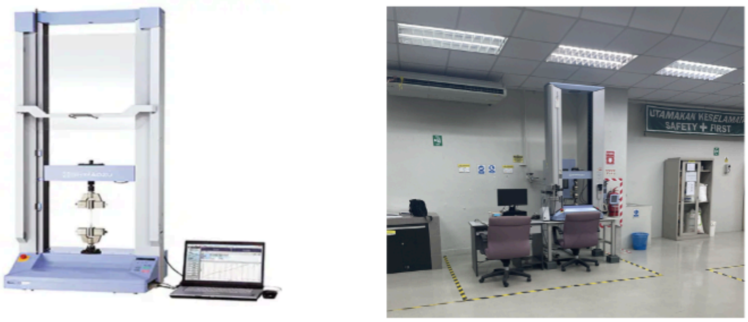


Fig. 8. Universal Testing Machine by Shimadzu at laboratory of Universiti Teknologi Malaysia, Kuala Lumpur

The Universal Testing Machine above features automatic reading of load cell characteristics, with real-time displays for test force, stress, stroke, and position. It also includes an external analog output with two channels. The digital display offers a resolution of 0.001 mm. Key specifications of the equipment used for dataset development are in Table 1.

Table 1
Specification to universal testing machine

Item	Description
A Maximum load capacity	20 kN
Crosshead maximum return speed	2200 mm/min
Crosshead speed range	0.001 to 1600 mm/min
Calibration	Automatic test force calibration (tensile, compression, or combined tests)
Measurement accuracy	Standard precision type (1/500)
Force accuracy	High-precision type (1/500)

Data from these tests were used as inputs for simulation predictions via Ansys software, aiming to replicate failure behavior observed experimentally and validate simulation benchmarks. Simulation is incorporating the characteristics of polypropylene (PP) as shown in Figure 9.

Typical Resin Properties	Unit	Product Data	ASTM Method
Melt Flow rate, at 230ºC	g/10min	11	D 1238
Density	g/cm^3	0.9	D 1505
Tensile Strength at Yield	kg/cm^2	360	D 638
Elongation at Yield	%	12	D 638
Flexural Modulus	kg/cm^2	17000	D790 B
Notched Izod Impact Strength at 23ºC	kgcm/cm	3.3	D 256A
Heat Deflection Temperature at $4.6kg/cm^2$	ºC	95	D 648
Rockwell Hardness	R scale	94	D785 A
Water Absorption after 24 Hours	%	0.02	D 570

Fig. 9. Polypropylene and its material properties [7]

The simulation work for this research is conducted using Simulation Software (Student Version), a widely recognized platform for advanced engineering analyses. The detailed hardware specifications of the laptop, which ensured efficient processing, accurate modelling, and reliable results, are provided in Table 2.

Table 2
Equipment and software specifications

Item	Description
Central Processing Unit (CPU)	AMD Ryzen 5 5600x
Graphical Processing Unit Random	NVIDIA GeForce RTX 3070 8GB
Access Memory (RAM)	16GB DDR4 3200MHz
Storage	1TB Solid State Drive (SSD)
Operating System (OS)	Windows 11 64-bit

The combination of stresses that leads to yielding is described by a yield criterion. For this study, the material is assumed to be ductile and isotropic, exhibiting identical behaviour under both tension and compression. A commonly used failure criterion based on distortional strain energy is the Von Mises Yield Criterion (also known as the Maximum Distortion Energy Theory). In the Ansys simulation, the strain energy density is calculated as $u = \frac{\sigma\varepsilon}{2}$. By applying Hooke's law, Von Mises' criterion can be derived, as detailed in [8]. The Von Mises equivalent stress is expressed as:

$$\sigma_{vm} = \sqrt{\sigma_{11}^2 - \sigma_{11}\sigma_{22} + \sigma_{22}^2} = \sqrt{\sigma_{xx}^2 - \sigma_{xx}\sigma_{yy} + \sigma_{yy}^2 + 3\tau_{xy}^2} =\leq \sigma_Y \quad (1)$$

Where $\sigma_{xx}, \sigma_{yy}, \tau_{xy}$ stated as a biaxial stress system in two directions and shear stress while stresses of σ_{11}, σ_{22} known to be the principal stress. The material yields when the applied stress reaches the yield stress. Following this, data validation is completed by comparing results from both experimental and simulation testing. Finally, the beauty company is help by a recommendation for improved solutions, including creating a more sustainable product packaging. In addition to enhancing quality, the research explores new types of sunscreen packaging as alternatives to the existing design. The updated packaging will also focus on being visually appealing and suitable for the target market.

3. Results

Understanding how stresses are distributed and behave under applied forces is critical, especially when a material interfaces with weaker regions or surfaces. The yield point is a key indicator of when permanent deformation begins can be identified using a typical stress-strain curve generated during compression testing. Figure 10, adapted from Solid Mechanics [8], illustrates the mechanical behavior of ductile materials. While the figure specifically addresses ductile materials, the principles outlined are broadly applicable across various material types. The stress-strain diagram in Figure 10 is segmented into four main stages: the elastic region, yielding phase, strain hardening phase, and necking phase. Each stage represents a critical aspect of the material's mechanical response under load, reflecting its ability to sustain stress without failing or deforming excessively.

Predicting potential failure modes and designing for safety requires an understanding of material brittleness. Brittleness is the tendency of a material to fracture with minimal plastic deformation. It is a crucial factor in material selection, failure analysis, and engineering safety. Materials exhibiting high brittleness typically offer limited resistance to impact and poor energy absorption [9]. Brittle plastic analysis, therefore, involves mechanical testing to understand how such polymers behave under stress, highlighting their functional boundaries. Among plastic materials, thermoplastics like

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polypropylene (PP) are commonly used due to their cost-effectiveness, low density, versatility, and relatively high heat distortion temperature [10,11].

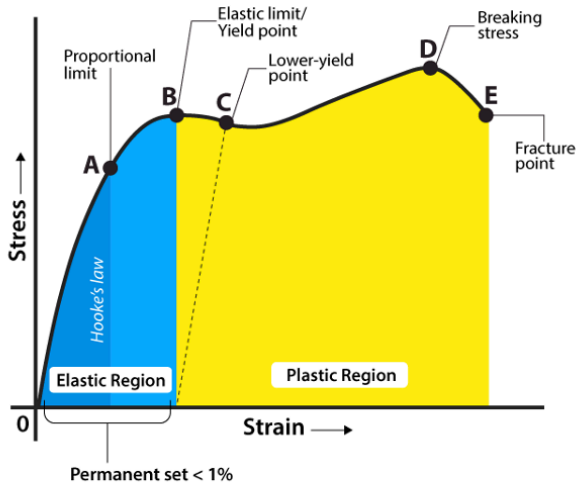


Fig. 10. The stress-strain diagram for ductile materials [8]

Brittle fracture is particularly problematic, characterized by sudden, catastrophic failure with minimal warning or plastic deformation. Simulation results, as presented in Figures 11 and 12, reveal significant stress concentrations and deformation. The stress-strain curve in Figure 13 further confirms the brittle behavior, showing patterns consistent with unpredictable failure which a typical hallmark of brittle materials.

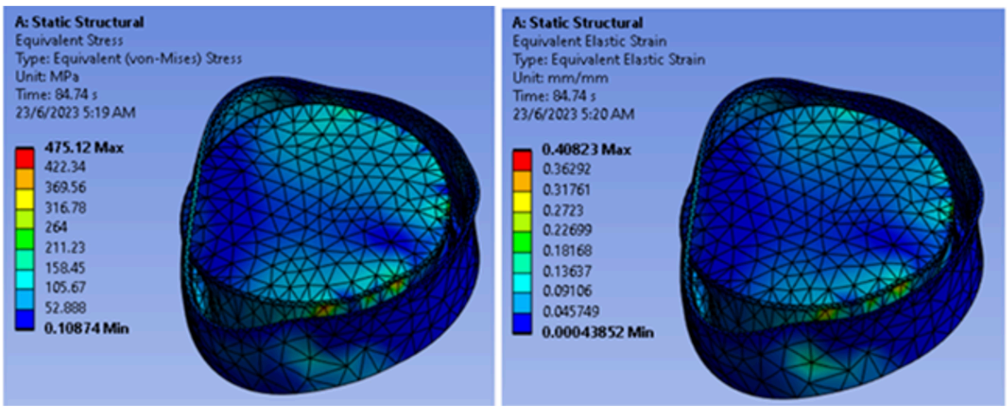


Fig. 11. Simulated stress and strain distribution illustrating areas of stress concentration

Critically, safety factor values around the lid area fell below 1, as shown in Figure 13, indicating a high risk of structural failure in this region. This aligns with simulation outcomes, which predicted failure in the outer lid. Notably, from experimental testing validated the simulation results, as illustrated in Figure 14. Both tests exhibited an identical "butterfly" failure pattern, supporting the conclusion that the material lacks sufficient ductility.

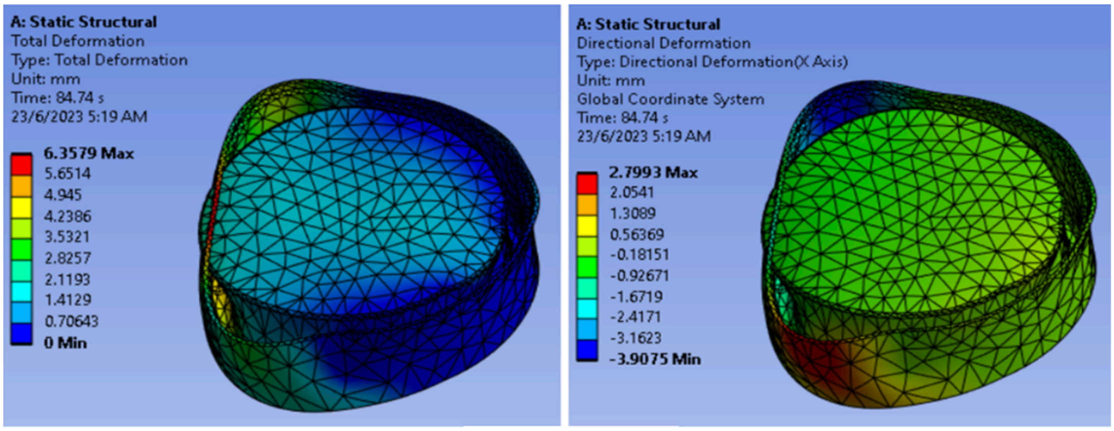


Fig. 12. The simulated displacement distribution on the sunscreen

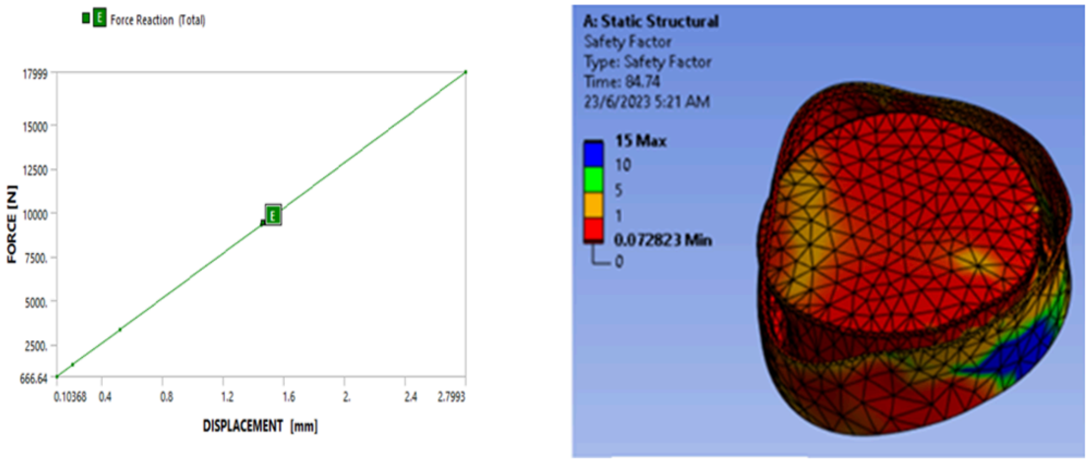
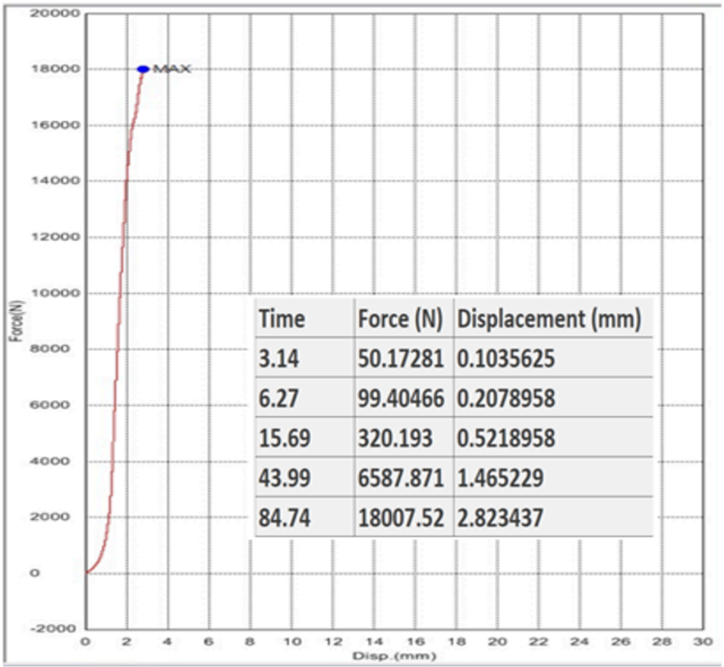


Fig. 13. Stress-strain curve and corresponding factor of safety (FOS) from simulation

Fig. 14. The experiment testing results using universal testing machine

Figure 15 confirms the material's brittle nature, reinforcing that it is unsuitable for components subject to sudden or repeated mechanical loads. The lack of energy absorption capacity is a fundamental limitation, and in this case, was identified as the root cause of packaging failure in the sunscreen product manufactured by the beauty company.



Time	Force (N)	Displacement (mm)
3.14	50.17281	0.1035625
6.27	99.40466	0.2078958
15.69	320.193	0.5218958
43.99	6587.871	1.465229
84.74	18007.52	2.823437

Fig. 15. Experimental stress-strain curve obtained using the universal testing machine

In response to customer feedback emphasizing sustainability, a shift toward more environmentally friendly packaging has been initiated. Alongside improved sustainability, the redesigned packaging is expected to offer better durability and quality, as depicted in Figure 16.

Fig. 16. Proposed tube-format packaging design for the new sunscreen product

To ensure the new sunscreen cover meets performance requirements, materials with low brittleness and low light transmittance are necessary. Based on a comprehensive literature review, Polyethylene Terephthalate (PET) is recommended as a suitable alternative. PET offers several benefits for this application, including high strength, light weight, excellent shatter resistance, and low gas permeability. Additionally, it exhibits low light transmittance, with polypropylene demonstrating complete UV absorption between 200 nm and 310 nm, as noted by Müller et al. (2023) [4]. The new design features a compact, waterproof tube format that maintains the original 10 ml volume, unchanged as capacity was not an issue. Aesthetically, light-colored packaging is preferred for its modern, clean appearance. Tube packaging, as highlighted in [12–16], offers several advantages in the cosmetics industry, including practicality, ease of use, and visual appeal.

4. Conclusions

The root cause of the sunscreen packaging failure was effectively identified through a combination of simulation and experimental analysis. Simulation results demonstrated that the Von Mises strain closely matched the maximum principal elastic strain, indicating localized material failure in the outer cap. This was further supported by low factor of safety values observed across the lid, confirming its inability to withstand the applied loads. Experimental testing, conducted using a Universal Testing Machine, verified that the cap material failed in a brittle manner. These tests revealed that the aluminium cap functioned primarily as a decorative element, offering minimal structural support. The strong alignment between simulation and experimental findings validates the diagnosis and confirms that the brittle nature of the cap material was the primary cause of leakage and mechanical failure. This study emphasizes the critical importance of accounting for brittleness during material selection, as brittle materials typically lack the ability to absorb impact or dissipate energy, making them unsuitable for components subjected to sudden or repeated stress. It also highlights the necessity of anticipating potential failure modes and incorporating adequate safety margins in the design phase to ensure reliability and long-term performance.

The simulation clearly exposed structural vulnerabilities in the cap design, reinforcing the need for enhanced material selection and improved engineering. Based on a thorough literature review, Polyethylene Terephthalate (PET) is recommended as a more suitable material. PET offers key advantages for this application, including high strength, lightweight properties, excellent shatter resistance, and low gas permeability. Beyond the technical insights, the investigation uncovered broader systemic issues such as poor material traceability and insufficient oversight in procurement and production processes. To address these challenges, the study recommends sourcing verified materials, redesigning the cap for improved durability, and adopting a more customer-focused approach to packaging development. Ultimately, this case highlights the essential role of packaging integrity that not only in preventing product failure, but also in maintaining brand trust, enhancing customer satisfaction, and supporting operational efficiency in an increasingly competitive market.

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