Design, Fabrication and Validation Report – Captain America Shield

1. Project Context

This project consists of the design and fabrication of a Captain America shield intended for real use in active character performances, where the object must withstand constant handling, sudden movements, and light impacts, while maintaining an appearance faithful to the original prop.

Before starting the design, a review of existing models available online was conducted. Some commercial designs featured basic modularity based on concentric rings glued onto curved plates. While this reduced weight, it introduced relevant issues for 3D printing and real-world use: visible tolerances, light leakage between joints, and low structural reliability at attachment points.

Other models, although visually appealing, prioritized organic modeling without considering additive manufacturing criteria, layer orientation, or the mechanical resistance of the final assembly.

Given these limitations, a fully original model was designed from scratch in SolidWorks, prioritizing: - Geometric precision and aesthetic fidelity - Structural reliability in real use - Optimized modularity for 3D printing - Resource reduction through lightweight design principles

The project was not conceived as a decorative piece, but as a functional object manufacturable with a domestic FDM printer, serving as a practical exercise in applying concepts of mechanics of materials, parametric design, and digital manufacturing.

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2. Design Objectives

Before modeling any geometry, clear design objectives were defined to guide all subsequent CAD, partitioning, fabrication, and assembly decisions. These objectives were functional and manufacturable, considering real use and FDM printing limitations.

General Objective

To design a functional and resistant Captain America shield optimized for domestic FDM 3D printing, capable of withstanding active handling and light impacts, while maintaining aesthetic fidelity and reducing resources through lightweight design principles.

Specific Objectives

1. **Structural reliability in real use**
   Ensure that the shield supports its own weight, sudden movements, and constant handling without relying exclusively on adhesives, especially in the strap mounting area.

2. **Functional modularity (not only aesthetic)**
   Divide the design into modules with clear functions: main structure, decorative rings, star base, and central star, allowing:
   - Painting by parts without extensive masking
   - Repairability and section replacement
   - Dimensional control during printing

3. **FDM printing optimization**
   Each module was designed considering:
   - Favorable layer orientation for mechanical loads
   - Reduction of critical overhangs
   - Elimination of unnecessary supports
   - Printing on a domestic printer without special modifications

4. **Avoid visible concentric joints and aesthetic tolerances**
   Unlike other reviewed models, the design avoids ring-on-plate constructions that create light gaps, visual discontinuities, or excessive dependence on surface bonding.

5. **Scalable parametric design**
   Design equations were implemented to allow modification of the total shield diameter without losing clearances, fits, or structural reliability, enabling future size variants.

6. **Separation between aesthetics and structure**
   Ensure that aesthetic elements (colors, finishes, visible parts) do not compromise structural integrity, maintaining resistance in the design core.

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3. Structural Decisions and Design Evolution

From the beginning, joints between the shield's structural parts were conceived as adhesive-assisted joints rather than rigid mechanical joints. The twelve sections forming the Shield rely mainly on a combination of E6000 and cyanoacrylate adhesives, supported only by geometric alignment guides, without initial use of pins, screws, or other locking elements.

This decision was intentional. The original goal was to allow slight joint deformation so the assembly could dissipate stresses from repetitive handling, vibrations, and sudden movements, reducing stress concentration typical of fully rigid FDM joints. E6000 was selected for its flexible behavior under dynamic loads, while cyanoacrylate was used for positional fixation during curing.

During assembly, reasonable concerns arose regarding the strong reliance on adhesive bonding, especially considering the shield's size and active use. These concerns were based on risk assessment rather than observed failures.

Empirical validation showed positive results. The final shield, delivered and used under intended conditions, shows no cracks or failures at adhesive joints even after prolonged real use. This confirmed the functional validity of the initial decision.

Nevertheless, the process provided a key learning: although adhesive joints performed well, the design could benefit from additional structural redundancy. Consequently, the CAD was later modified to include auxiliary geometric elements (small parallelograms and internal interlocks) that work together with the adhesive, sharing loads and improving long-term reliability without eliminating joint flexibility.

This evolution represents an informed design iteration based on practical experience and observation of real behavior, aligning with an engineering design approach applied to additive manufacturing.

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4. Fabrication and Practical Validation

The shield was fabricated entirely using FDM 3D printing on a domestic printer with Creality PLA+ material. Real equipment limitations directly influenced design, partitioning, and orientation decisions.

4.1 General Printing Parameters

- Material: Creality PLA+
- Layer height: 0.3 mm
- Total printing time: approximately 46 accumulated hours

The relatively large layer height was chosen to reduce fabrication time, at the expense of increased sanding work. This tradeoff reinforced the importance of evaluating the entire process, not just printing time.

4.2 Manufacturing Issues Encountered

During printing of the Shield sections, the printer exhibited an uncorrected "elephant's foot" effect. While manageable in individual prints, its cumulative impact was underestimated.

During assembly, a radial mismatch of approximately 5 mm appeared along the outer arc, resulting from accumulated dimensional deviations across all sections.

Manual correction was performed using failed print material and a soldering iron to adjust the perimeter. Although effective, this highlighted the critical importance of dimensional calibration when working with modular geometries.

Permanent corrective actions included both precise bed calibration and replacement of springs with silicone spacers to improve dimensional stability.

4.3 Practical Validation

Despite limitations and corrective actions, the assembled shield was delivered and used in real conditions. It withstood its own weight, active handling, sudden movements and light impacts.

Without structural failures, cracks, or joint detachment. This validated the adequacy of the design and fabrication decisions for the intended use.

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5. Assembly and Structure

Assembly was treated as a critical structural stage rather than a simple final joining step. Given the shield's size, active use, and modular design, assembly strategy directly affected mechanical reliability.

5.1 Assembly Strategy

Assembly was performed progressively, starting with reconstruction of the Shield from its twelve radial sections. A combination of E6000 and cyanoacrylate was used E6000 as the primary flexible load-absorbing adhesive and Cyanoacrylate for initial fixation during curing.

Integrated geometric guides ensured proper alignment even without rigid mechanical fasteners.

From an FDM perspective, part orientation ensured wall–layer interfaces at joints, where initial layers of one part contacted multiple external walls of the adjacent part. This created a three-dimensional bonding region, avoiding pure layer-to-layer joints and enabling better load transfer.

5.2 Structural Joint Evolution

Post-assembly analysis showed that although adhesive joints functioned correctly, part of the structural load depended heavily on initial printed layers, which are among the weakest planes in FDM parts.

As a result, the design was evolved to include auxiliary PLA+ parallelogram elements, allowing load transfer across a larger number of layers and solid volume. Adhesives thus distribute loads across multiple active layers, reducing dependence on the critical interlaminar plane.

This change complemented flexible adhesives while increasing overall reliability.

5.3 Straps and Grip Area

The strap area posed the greatest structural challenge. Located on the concave inner surface, its geometry required careful consideration of:

- Curved surface offsets
- Layer orientation favorable to tensile and bending loads
- Thickness compatible with FDM printing without compromising strength
- Initially designed to rely mainly on two-part epoxy, uncertainty regarding real adhesive–print interface behavior led to a hybrid solution.

Through-bolted stovebolts with washers and nuts were added, passing through the shield and strap mounts. This modification was applied directly to the printed part and later incorporated into the CAD model.

This introduced structural redundancy:

- Adhesive distributes loads and reduces stress concentration
- Mechanical fasteners ensure integrity under partial failures or unexpected loads

5.4 Structural Result

The assembled shield supports its own weight, prolonged active handling, sudden movements, and light impacts without joint failure, strap detachment, or permanent deformation. The result confirms that the assembly strategy is appropriate for the intended real use.

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6. Finishes and Aesthetic Decisions

Finishing was treated as an extension of functional design, recognizing that aesthetic decisions affect durability, maintenance, and perception. Modular construction allowed finishing by parts prior to final assembly, reducing masking complexity.

Rust-Oleum and Montana metallic paints were used for primary colors, with Rust-Oleum satin clear coat for protection. This combination achieved a balance between metallic appearance, contrast, and surface protection.

Manual sanding reduced layer marks from 0.3 mm printing. While time-consuming, it achieved acceptable visual quality.

No structural coatings such as polyurethane were applied, as they would negatively affect the desired metallic matte finish. This reflects a conscious tradeoff between protection and aesthetics.

The final result is a fully functional prototype fabricated under realistic domestic printing conditions and validated in real use.

7. Project Limitations

7.1 Simulation and Modeling Limitations

- No full FEM simulation was performed due to inability to reliably model the real wall–adhesive–first-layer interface.
- Adhesives exhibit viscoelastic, process-dependent behavior difficult to represent with isotropic properties.
- FDM anisotropy and varying layer orientations prevent representative global modeling.

For the reasons stated above, numerical analysis was therefore limited to critical components such as straps and load-transferring elements.

7.2 Experimental Validation Limitations

- No controlled destructive tests or standardized fatigue tests were conducted.
- Validation is based on repeated real use, visual inspection, and absence of in-service failures, which does not replace laboratory testing.
- No load, acceleration, or deformation measurements were instrumented.

7.3 Design Limitations

- Initial design relies mainly on flexible adhesive joints without geometric redundancy, which may be unsuitable for severe loads or high-energy impacts.
- Structural performance depends on correct adhesive application and print quality.
- The design is optimized for a specific diameter and use conditions; scaling requires revalidation.

These limitations define the project's valid application domain and establish a basis for future improvements.

8. Conclusions

The Captain America shield development integrated mechanical design, additive manufacturing, and real-use validation, resulting in a functional object meeting resistance, aesthetic, and manufacturability requirements.

The design process demonstrated that flexible adhesive joints, even without initial geometric redundancy, can be sufficient for a well-defined load scenario, provided there is clear understanding of the real FDM joint interface and proper process control.

The absence of structural failures during prolonged real use validates the adopted design decisions, particularly load distribution and prioritization of critical elements. Selective FEM analysis proved more honest and effective than attempting full-system modeling under unrealistic assumptions.

The project highlights the importance of acknowledging modeling limitations when working with non-ideal processes such as FDM printing and viscoelastic adhesives, reinforcing the need to complement theory with real-world validation.

Finally, this work produced not only a functional product but also a valuable formative exercise, driving design evolution toward hybrid solutions and establishing a strong foundation for future high-demand functional 3D printed objects.