Digital Vault Systems for Low-Energy and Material-Efficient Construction: BlenderVault; A Design-Driven Form-Finding Approach

Abstract

The construction industry accounts for a significant share of global material consumption and energy use, prompting renewed interest in structurally efficient architectural systems that minimize waste. Vaulted structures, particularly those primarily working in compression, have historically demonstrated outstanding material efficiency and durability. However, their contemporary application remains limited due to complex design processes and a lack of accessible digital tools that integrate structural logic with architectural design.

This paper explores a design-driven approach to digital vault systems aimed at low-energy and material-efficient construction. It presents the development of a computational workflow that supports early-stage form-finding of vaulted structures using geometric reasoning rather than heavy numerical optimization. Employing triangulation-based mesh logic and designer-defined base points, the method enables the generation of compression-oriented forms while allowing direct control over spatial and architectural parameters.

A prototype tool developed in the Blender environment is presented as a case study. The tool allows designers to explore various vaulted configurations by adjusting base conditions, height, applied forces, and mesh density, providing immediate visual feedback during the conceptual phase. Rather than replacing structural analysis, the workflow supports informed decision-making where sustainability considerations exert the greatest influence on design outcomes.

The findings suggest that embedding intuitive form-finding methods in widely used modeling platforms can lower the barrier to adopting structurally efficient vault systems. The paper concludes by discussing the potential of such systems for sustainable construction, digital fabrication, and future research directions, including structural optimization and circular design strategies.

Keywords: Digital vaults; sustainable construction; form-finding; material efficiency; architectural geometry; compression structures, Blendervault

1. Introduction

The building sector is a key contributor to global energy consumption and material use, making it central to sustainability-oriented research in architecture and construction. Conventional structural systems often rely on material-intensive solutions and energy-demanding processes that heighten environmental impact. Consequently, structurally efficient systems capable of delivering spatial and architectural performance with reduced material input have regained importance.

Vaulted structures exemplify one of the most materially efficient structural typologies developed throughout history. Working primarily in compression, traditional masonry vaults achieve stability through geometry rather than material strength, ensuring durability and low maintenance. Despite these advantages, their use today is mostly confined to restorations or iconic projects due to design and construction complexity.

	
Ruins of Arch of Ctesiphon pictured in 1864	*The "Droneport" vault construction at the Norman Foster Foundation Pavilion*

Recent advancements in computational design and digital fabrication have reignited interest in compression-based systems. Tools such as graphic statics and form-finding techniques allow designers to explore geometries that align structural logic with form. Yet, many existing approaches require specialized software or advanced structural expertise, limiting accessibility during early design stages.

This research asserts that integrating intuitive form-finding methods into familiar design environments can significantly enhance the deployment of vaulted systems in low-energy construction. It emphasizes a design-driven approach that empowers architects to make informed geometric choices in the conceptual phase—when sustainability and efficiency have the greatest impact.

The study aims to develop a digital method combining geometric clarity, structural logic, and architectural control. Implemented within Blender, the proposed workflow demonstrates how triangulation-based mesh systems and boundary conditions enable the generation of compression-oriented vaults suitable for sustainable, material-efficient construction.

2. Background and Related Work

2.1 Vaulted Structures and Material Efficiency

Vault and arch systems have long exemplified structural efficiency in masonry, where compressive strength vastly exceeds tensile capacity. Historical precedents show that geometric form governs stability, enabling wide spans with minimal material. Such geometry-driven systems are inherently sustainable due to their low embodied energy and long life cycle.

However, modern industrialized construction favors flat slabs and frame-based systems that prioritize standardization and speed. This shift has led to a loss of knowledge about compression-based systems, especially in early-stage design workflows.

2.2 Form-Finding and Compression-Only Structures

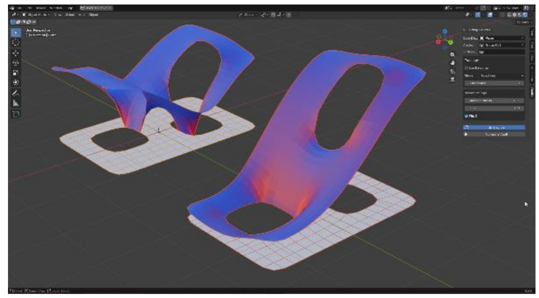
Form-finding determines geometries that achieve equilibrium with minimal bending or tension. Classical hanging chain models inspired this field by revealing how natural force paths produce stable, compression-only shapes. Digital form-finding extends these principles into computational spaces through tools like graphic statics, emphasizing geometry and equilibrium over complex numerical analysis. Yet, many tools remain engineering-centric, creating a disconnect from architectural intuition.

2.3 Digital Tools for Vault Design

Notable tools such as RhinoVAULT have made thrust network analysis accessible for exploring compression-only geometries through interactive graphic statics (Rippmann, Liew, & Block, 2014). Similar efforts demonstrate progress in integrating structure-aware design with digital fabrication. However, most tools operate within commercial specialized software detached from everyday design workflows, reducing their impact on early conceptual design where material efficiency matters most.

2.4 Research Gap

The literature reveals a gap between structurally informed methods and design-oriented environments. Few approaches embed intuitive form-finding directly within widely adopted 3D modeling open-source tools. This research addresses that gap by integrating geometric clarity, direct manipulation, and conceptual design reasoning into Blender3D—reconnecting vaulted structural logic with contemporary architecture.

	
RhinoVault- A leading vault form-finding tool, based on Rhino 3D (Commercial package)	*BlenderVault – Open source simple funicular form-finding tool, using Blender3D*

3. Methodology

3.1 Design-Driven Research Framework

The methodology follows a design-driven framework where computational logic aids architectural decisions in early stages. The focus lies in geometric reasoning rather than numerical optimization to generate compression-oriented forms while maintaining careful control over parameters such as span, height, and supports.

3.2 Geometric Representation and Base Conditions

Designers define base points representing structural supports, which serve as anchors for boundary geometry and establish initial force flow. A triangulated mesh discretizes this geometry, ensuring stability, adaptability, and compatibility with fabrication methods.

3.3 Fan Subdivision Strategy

Fan subdivision distributes triangles radially around base points, enhancing mesh regularity and emphasizing structural logic. It allows local refinement without increasing global mesh density, maintaining computational efficiency during exploration.

3.4 Delaunay Triangulation and Mesh Optimization

Subsequent Delaunay triangulation produces a coherent surface by maximizing minimum triangle angles, preventing distorted mesh geometries and supporting smooth curvature for funicular behavior.

3.5 Height Control and Form-Finding Logic

A global height parameter constrains vault rise and enables multiple geometric variations without altering boundary conditions. While not a full structural analysis, this approach promotes compression-oriented shapes suitable for later validation.

3.6 Implementation Environment

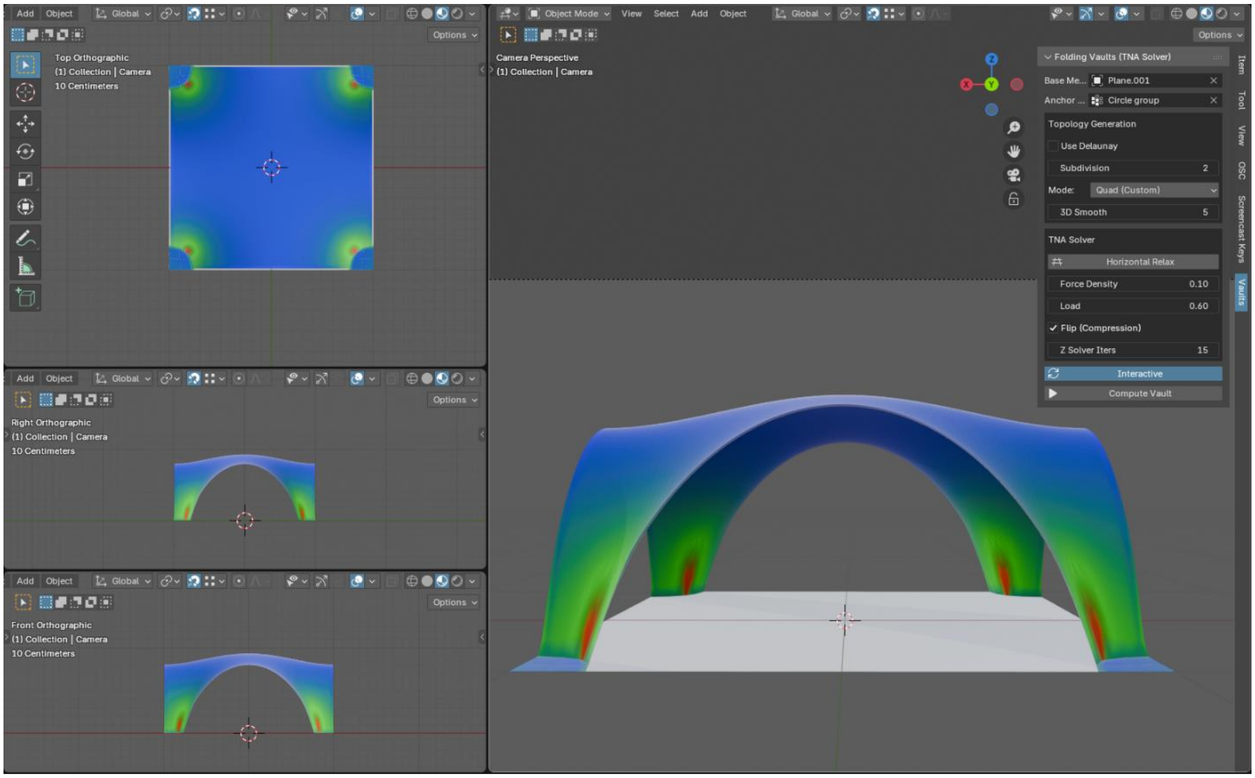
The prototype tool, **BlenderVault**, was implemented in Blender3D—selected for its open-source accessibility, mesh manipulation capabilities, and growing use in architecture. Real-time interaction with parameters such as base points, height, and mesh density fosters iterative, sustainability-aware design exploration.

4. Prototype Case Study: Single Vault System

A single-vault scenario tested the workflow's usability and geometric coherence. Designers manipulated base points and parameters interactively, observing resulting funicular geometries.

The resulting vault displayed continuous curvature and clearly legible force paths. While no explicit structural analysis was conducted, the geometry exhibited compression-dominant characteristics. This demonstrates that geometric reasoning alone can generate efficient vaults suitable for subsequent refinement and fabrication-aware modeling.

Limitations include the absence of load calculations and the focus on static configurations, which will be addressed in future work.



Inspired by the "Droneport" vault construction at the Norman Foster Foundation Pavilion, this form is generated by the BlenderVault.

5. Discussion

The proposed workflow enhances **design agency**, allowing architects to engage with structural behavior during early design. This increases awareness of material and energy efficiency while preserving creative flexibility.

From a sustainability viewpoint, geometric reasoning supports compression-dominant designs that minimize material use and energy demand. Embedding this process in an accessible tool like Blender democratizes form-finding for both professionals and students, fostering widespread integration in design education.

However, the lack of explicit force validation means the workflow must complement, not replace, engineering analysis. Expanding it to multi-vault systems and diverse material contexts represents a natural continuation of this work.

6. Conclusion and Future Work

This research introduces an accessible, design-driven method for digital vault generation supporting low-energy, material-efficient construction. Combining fan subdivision, Delaunay triangulation, and interactive controls within Blender enables compression-oriented geometry exploration at conceptual stages.

Key outcomes include:

1. Integration of architectural and structural logic.
2. Demonstrated potential for material-efficient design.
3. Lowered accessibility barriers for design professionals and educators.

Future research should advance the prototype by incorporating numerical verification, extending it to multi-vault configurations, adapting it for fabrication workflows, and exploring parametric adaptability. These developments could transform the tool into a comprehensive design and education platform promoting sustainable, computationally informed architecture.

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