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Mycelium Biocomposite Based Façade System Optimization for Landslide-Resistant Structure in Yunnan Mountainous Region

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Abstract. This project develops a landslide-resistant façade system in Malong District, Yunnan, unleashing the buffering properties of Mycelium Biocomposites (MBC). A novel digital model that combines Rigid Body Dynamics (RBD), Finite Element Analysis (FEA), and Evolutionary Algorithm (EA) to optimize an MBC-based material system under landslide impact. This model integrates MBC (as a flexible layer) with a concrete framework (as a rigid layer) to form a composite model that accurately simulates building responses to landslide impacts. The approach is adaptable, scaling from single buildings to entire villages, and aligns with varying risk levels. This innovative use of MBC advances sustainable and resilient architectural design in landslide-prone regions.

Keywords. Mycelium Biocomposite (MBC), Landslide Impact Simulation, Landslide-Resistant Structure Optimization

1. Introduction

Landslides, a prevalent natural hazard in mountainous areas, often involve the movement of massive rocks and heavy debris (Kanungo et al., 2008) These hazards can cause severe damage to slopes, infrastructures, and buildings, resulting in casualties and economic loss (Barla & Antolini, 2016). Over the past two decades in Malong District, Qujing City, Yunnan Province in China, landslides have been particularly destructive, affecting more than 8,000 individuals (Bai et al., 2023). In the face of disaster, while efficient slope stabilization is vital, sturdy building protection stands as the final safeguard for safeguarding lives (Zhu et al., 2019).

Landslide-resistant building structures should adhere to two key principles: rigid protection and flexible protection (Zhao, 2021). The current method of analysis and simulation of landslides typically contains physical experiments and numerical simulations. However, physical experiments often test only a single component, neglecting the integrity of the entire building structure and failing to accurately reflect

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its real-world performance. Numerical simulations, while offering precise and reliable results, usually concentrate on analysing either rigid or flexible measures in isolation (Luo et al., 2019), without integrating both approaches into a consolidated model. Additionally, the impact of a real landslide flow is a complex non-linear dynamic event, and both of these methods fail to accurately simulate. Therefore, to more realistically model the unique impacts of landslide flows and apply these impacts for optimizing building design, it is essential to construct a dynamic form-finding composite structural system under landslide impact.

In this study, we introduce a novel workflow combining Rigid Body Dynamics (RBD), Finite Element Analysis (FEA), and Evolutionary Algorithm (EA) to optimize MBC sandwich facade components against landslide flow impact. This approach integrates rigid and flexible protective measures, designing a structural system optimized through numerical simulation. The aim is to enhance the overall building's impact resistance capability.

A study in Malong District, Yunan, showcased the adaptability of a dynamic optimization model for creating landslide-resistant architectural systems. This efficient workflow can also incorporate customized materials for more complex composites and extends its utility to optimizing buildings for other extreme conditions such as snow loads, typhoons, and floods.

2. Background

2.1. RIGID AND FLEXIBLE PROTECTION ON BUILDINGS

Current landslide protection strategies for buildings focus on rigid and flexible methods (Zhao, 2021). Rigid protection involves measures to enhance buildings' stability, strength, or elasticity, enabling it to resist various external forces or impacts (Roth, 1981). Zhao's research highlights that the initial impact force of landslides carries the most energy, and buildings' survivability can be greatly enhanced by withstanding the first impact. Strengthening the main structure to resist the first impact of landslides is crucial, but direct exposure to impacts can lead to a domino effect, where the direct transfer of force causes axial deflection and creates damage to the column-grid structure (Mavrouli et al., 2014). Therefore, an additional buffer system that serves as flexible protection to absorb and disperse these forces is needed to provide elasticity, reduce the risk of chain reaction to minimize the likelihood of structural damage (Liu et al., 2017).

In theory, these principles aim to be complementary and integrated for detailed research and validation, but this process is inherently complex, especially regarding optimization. While there have been various precise methods currently, they still have certain limitations. For instance, Zhao's study developed comprehensive models integrating the main building structure to simulate landslide flow impact, but it lacks automatic optimization progress. Similarly, the research by Tiago and Julio (Tiago & Júlio, 2010) made significant strides in applying FEA and practical landslide engineering designs. These studies only consider the rigid protection and lack of integration of rigid and flexible effects on the building. Therefore, there remains a gap in creating an optimization cohesive system that effectively combines both rigid and flexible methods based on the given material system.

2.2. MYCELIUM BIOCOMPOSITES (MBC)

MBC, a novel substance that combines filamentous fungi with agricultural residues, is known for its renewable and buffering properties, is increasingly used in interior structures and packaging (Aiduang et al., 2022). MBC can form a dense network by digesting plant waste, offering unique, flexible protective qualities such as cushioning, biodegradability, and renewability (Attias et al., 2020).

However, relying solely on MBC to resist disaster impacts is challenging due to its lower load capacity and potential for displacement. These can be addressed by using "Sandwich Panels" that merge the benefits of wood and MBC. In the "mycelium biocomposite sandwich panel," wooden boards form the external layers, offering essential bending strength and rigidity. At the core of the panel is MBC, which distributes stress evenly across the structure, while providing both lightweight and cushioning properties(Saez et al., 2022). With the studies from (Özdemir et al., 2022), these panels show improved bending and compressive strength compared to MBC alone, making it suitable for architectural components and applications requiring higher bending strength. To assess the MBC sandwich panel against traditional materials, expanded polystyrene (EPS) sandwich panels as a representative example is used for evaluation. Material physical experiments showed that The MBC panel exhibited minimal compression deformation, whereas the EPS demonstrated resilience to a compressive stress of 220000 N/m² (Ling et al., 2018). During shear testing, MBC panels endured a stress of 18900 N/m², whereas EPS withstood 100000 N/m² (Ling et al., 2018). Despite their similar compressive strength, MBC exhibited inferior shear strength. Nevertheless, considering factors such as carbon footprint, environmental impact and cost-effectiveness, MBC sandwich panel is the better option. As estimated, the production of the same volume of MBC has carbon emissions 1.5 to 6 times less than mass timber or bamboo(Duan et al., 2022), 10 times less than plastics and expanded polystyrene (EPS) (Hidalgo-Crespo et al., 2022). Additionally, its production benefits from Yunnan's mushroom cultivation, reducing material transportation needs. The next step of research is to establish an effective MBC-based structure system as a building envelope to withstand a certain landslide flow impact.

3. Research statement

Can we develop a structure optimization parametric model that can take MBC into the façade system and optimize under the landslide impact, while ensuring stability, cost-efficiency and adaptability in architectural design?

4. Methodology selection

To construct the façade optimization model under landslide impact (non-linear dynamic forces), we should apply RBD, FEA and EA.

Rigid Body Dynamics (RBD) is a numerical simulation method used to analyse the motion and behaviour of rigid bodies (Spurio, 2023). The Houdini Rigid Body Solver, a tool of RBD, can accurately and iteratively simulates object dynamic under external forces (Horsley & Stuart, 2019). In our landslide impact scenarios, it models water particles as colliding bodies, setting their velocities and directions to simulate collisions with buildings. RBD applies constraints to simulate internal interactions and combines particle forces into resultant forces for Finite Element Analysis (FEA), facilitating comprehensive impact assessment.

FEA is widely used in structural engineering to evaluate and predict the performance of building structures under various load conditions (Whiteley, 2014). In this project, FEA is embedded in Houdini to check overall stability, and non-linear dynamic analysis is performed to check the deflection of the building structure. The primary goal of structural optimization is to minimize deflection. Generally, more material in a structure can reduce deflection and increase stiffness. However, in practical design, the focus should not only be on strengthening the structure, but also on ensuring cost-effectiveness. The Multi-Objective Evolutionary Algorithm (EA) can optimize for minimal material use and deflection reduction by balancing multiple targets. In our study, it's feasible to use numerical simulations including EA, RBD, and FEA to develop a dynamic optimization workflow for creating landslide-resistant architectural structures.

5. Design development

Figure 1 shows the workflow of this study. Stage 1: setting up structures with rigid and flexible protection. Stage 2: multi-objective optimization including user-defined materials. Stage 3: selecting and expanding design paradigms across a village.

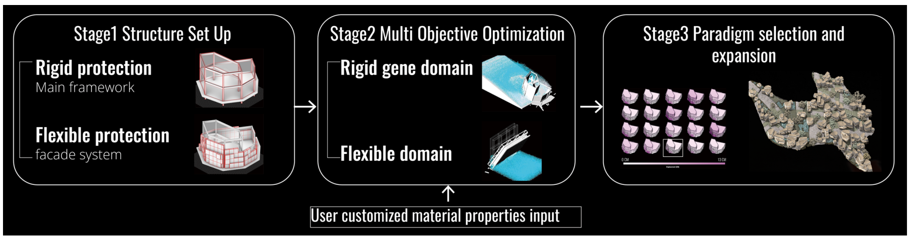

Figure.1 the workflow of landslide resistant structure optimization process

5.1. BASIC STRUCTURE SET UP

The following outlines the process of MBC sandwich façade system form driven by landslide impact. Initially, the building's morphology is modelled based on the vernacular building in Yunnan, with the main structure being a frame system. Following landslide-resistant principles, this frame structure mainly provides rigid protection and should have enhanced physical strength. The building's envelope, serving as flexible protection, acts as a buffer layer to absorb energy. It incorporates MBC sandwich components, whose layering is determined by the degree of deflection experienced in different building sections due to the impact. The greater the deflection, the more layers the sandwich component should have. This step is shown in Figure 2.

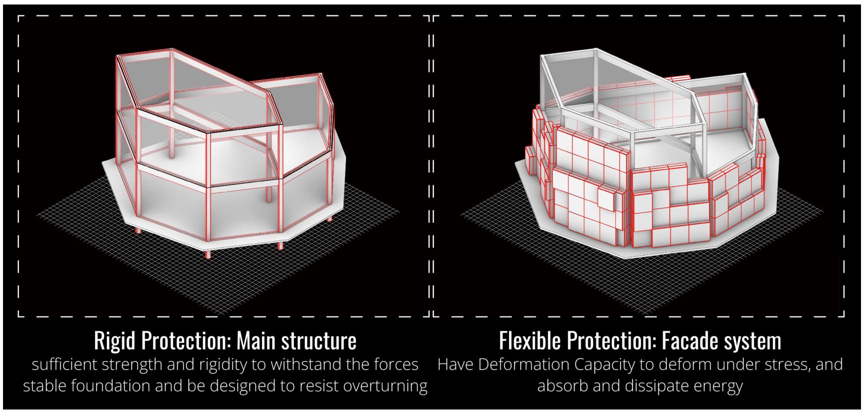

Figure.2 Structure set up contains rigid and flexible protection definition.

5.2. IMPACT ANALYSIS AND FAÇADE FORM FINDING

We combined Houdini's RBD and Water Flip systems for landslide impact simulation. The Water Flip system models water striking the building, recording and storing each particle's velocity, direction, and final position. Houdini's RBD system then transforms each water particle into a collision rigid body. The peak impact force of each individual particle is calculated based on formulas from the "Landslide Disaster Prevention Engineering Design Standards"(China University of Geosciences Press Debris Flow Prevention Engineering Design Specification, 2018):

$$F_f = \lambda \gamma_f v^2{}_f b_f h_f \sin \alpha / g$$

F_f is the mudflow slurry impact force (kN); v_f is the water velocity (m/s); γ_f is the mudflow capacity (kN/m3); b_f is the mudflow width (m); h_f is the mudflow depth (m); α is the angle (degree) between the facing surface of the building and the direction of the landslide. λ is the building shape factor. In this project, γ_f=17.248KN/m³, b_f = 9m, h_f=1.8m, $\alpha = 90°$, λ=1.33.

Using the parallelogram rule, the resultant force on each building surface is calculated and then broken down into a finer mesh using FEA. For MBC, we've inputted specific physical properties derived from our research and previous experiments: Young's Modulus dir1: 0.118 kN/cm² , Young's Modulus dir2: 0.114 kN/cm², In-Plane Shear Modulus: 1.9 kN/cm² , Transverse Shear Modulus dir1: 1.2 kN/cm² , Transverse Shear Modulus dir2: 1.1 kN/cm², Specific weight: 3kN/m³ , Tensile Strength dir1: 0.001kN/cm² ,Tensile Strength dir2: 0.003kN/cm², Compressive Strength: 0.102 kN/cm² . In our configuration, the material coefficients for MBC serve as a template. Our system allows users to modify and input different material properties according to their specific requirements.

In addition to customizing the physical properties of MBC sandwich panels, it is also needed to integrate the façade with the rigid structure (Beams and columns) to create support constraints. In this case, we use the parameters of C25 concrete physical property. FEA, developed in Houdini, checks overall stability and performs non-linear dynamic analysis for structural deflection. The calculation method is according to

Cairns 's research (Cairns, 2012).

The façade's deflection map guides the MBC layer distribution, with areas of higher deflection receiving more layers for enhanced stability. After MBC application, deflection is reassessed, and these values are used as targets in the EA optimization, where the number of MBC layers is a key genetic parameter (see Figure 3).

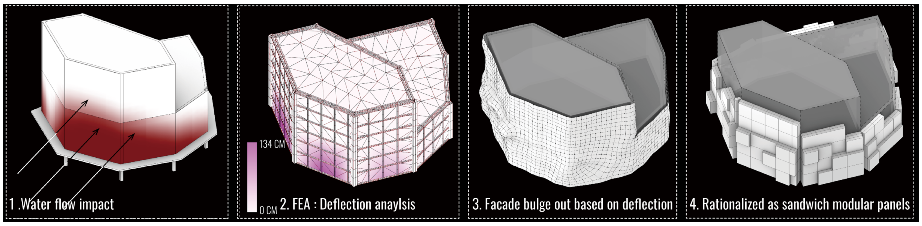

Figure.3 Landslide impact driven sandwich component relocation on facade

5.3. MULTI-OBJECTIVE OPTIMIZATION AND VALIDATION

Generally, more material typically enhances structural stability, but for cost efficiency, the goal is to achieve maximum stability with minimal material. Therefore, we define two objectives of EA: 1) Minimize displacement, and 2) Minimize material usage. The controllable genetic parameters are defined as follows: for the rigid structure, the dimensions (length, width, height) of beams and columns; for the flexible structure, the dimensions (length, width, height) and layer count of the MBC components.

Traditionally, these parameters might be determined by a designer's aesthetic intuition and design proportions, but in this study, they should be based on safety limits. This necessitates another round of RBD simulation to determine the size range for beams, columns, and MBC dimensions. Results indicate that for beams and columns, dimensions under 20cm are inadequate, while over 60cm show no extra benefit. For MBC panels, widths below 40cm are ineffective, and above 140cm offer no significant improvement, setting our size ranges (Figure 4).

The EA optimization process is integrated into Houdini's solver, which conducts 100 generations with 10 individuals each. Since EA generates a range of Pareto front solutions rather than a single optimal result, selection from these solutions is necessary. Despite subtle difference among these solutions due to fewer genes and objectives, it still causes vastly different impacts on the water flow.

Consequently, we chose four representative outcomes for further landslide simulation: the best for Objective 1, the best for Objective 2, and an average of both objectives. Among these, the average outcome was found to be the most resilient to landslide impacts.

5.4. STRUCTURE DEVELOPMENT

The assembly process involves modular components of sandwich protective envelopes installed into a customizable steel frame for easy dismantling and installation. The layers of these components can be adjusted according to user needs and environmental changes (Figure 5).

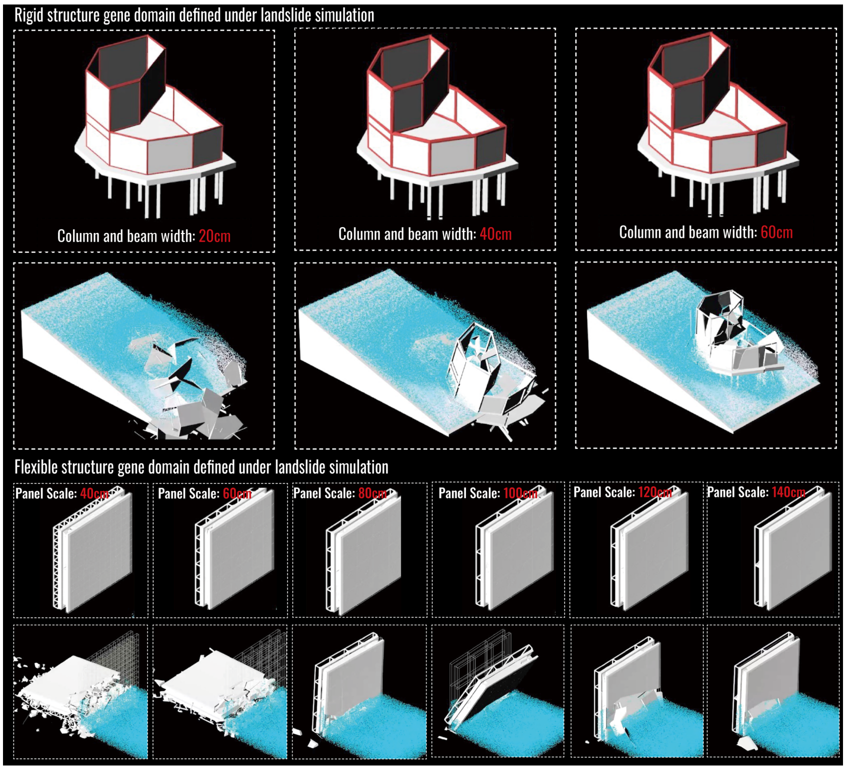

Figure.4 Rigid and flexible structure gene domain definition under water flow test

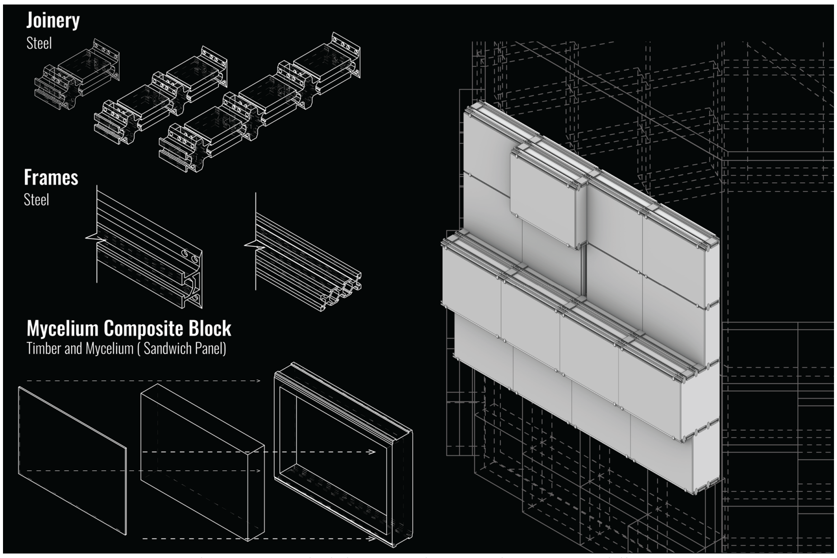

Figure.5 Sandwich protective envelopes assembling.

6. Results observation

The design and optimization of individual buildings integrate a combination of rigid and flexible structures, merging their physical properties into a cohesive model. Through RBD and FEA simulations, the impact of landslides on buildings is modelled, followed by EA optimization of the structure. The initial setting of gene parameter ranges ensures that all optimized designs stay within safe operational limits. The Standard Deviation Graph (Figure 6) shows both objectives improving steadily through generational iterations, and a shift in the curve to the left indicates better mean performance. During the iterative optimization process, the standard deviation (SD) graphs for FC1 and FC2 show a trend towards the left, indicating a reduction in both displacement and volume. However, after achieving a certain level of reduction, further significant changes cease to occur. This suggests that the optimization reaches a point of diminishing returns, where additional iterations do not result in substantial improvements in the parameters being optimized. Subtle but impactful variations were noted in the Pareto-optimal solutions due to limited genes and objectives in the EA, and it shows the results of each generation that best match the objectives. Four selected outcomes, particularly the one averaging both objectives, showed superior resilience in landslide simulations, highlighting the importance of computational modelling in detecting crucial, yet often imperceptible, variations (Figure 7).

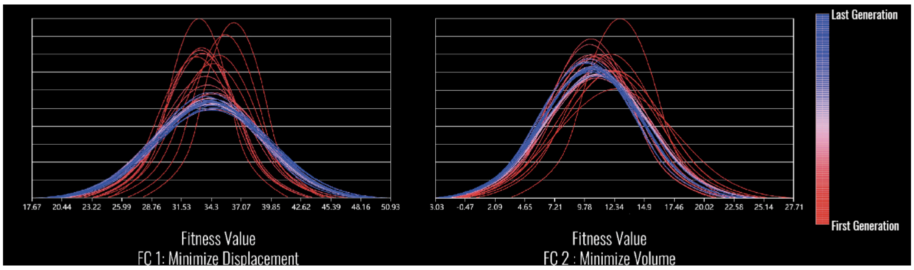

Figure.6 Standard Deviation Graph (Increased variation is represented through a ‘flat’ curve, while increased convergence is represented through a ‘narrow’ curve.)

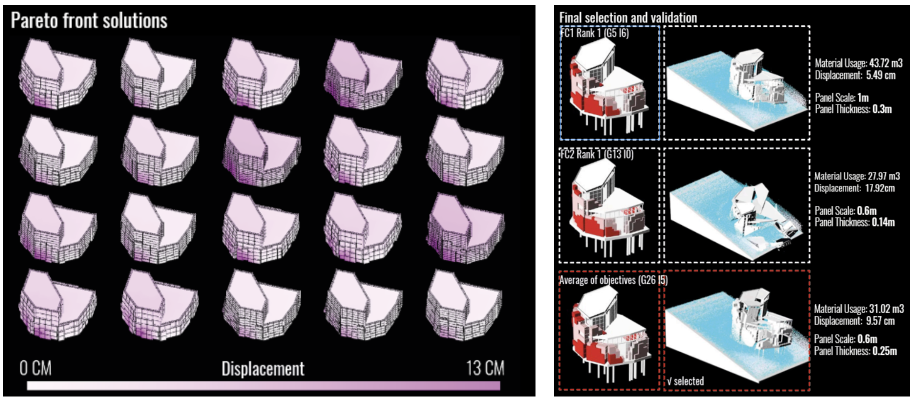

Figure.7 EA optimization results and final selection

In a village-wide application, we now expand this approach to cover all houses in a village. A detailed terrain analysis is conducted to create a landslide risk map, which then informs the distribution of MBC sandwich panels on buildings according to varying risk levels. The allocation of these panels is aligned with the degree of risk in different areas. The modular design of these panels allows residents to easily reconfigure, recycle, or replace parts, essential for adapting to fluctuating landslide risks and promoting sustainability (Figure 8).

Figure.8 Paradigm expansion

7. Limitations and conclusion

This research primarily focuses on building protection but overlook broader slope protection and urban infrastructure aspects. Future efforts will explore site-specific slope optimization to broaden landslide resilience strategies. Additionally, the current reliance on RBD for simulating landslide impacts on buildings does not account for the varied nature of landslide materials such as stones and mud, crucial for precise structural integrity assessment. Further research is needed to develop detailed simulations that consider the diverse materials in landslides and their specific impacts on buildings. Finally, the current focus of MBC design is on digital evaluation and optimization. To fully utilize its eco-friendly potential in structural engineering, future efforts must address its practical application, including production specifications, and integrate digital models into construction practices for specific projects.

This study showcases MBC sandwich panels and computational methods for creating landslide-resistant buildings, providing a dynamic, sustainable solution for extreme environments. It enables customization of material properties for complex systems and optimization in extreme conditions, supporting architects and designers in developing safer, resilient communities for future extreme environmental challenges.

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