ABSTRACT
In 2015, an earthquake of 7.8 magnitude displaced over 6.6 million people in Kathmandu, Nepal. Three years later, the country continues in its struggle to rebuild its capital. The aim of this study is to investigate a construction system, produced from locally sourced materials, that can aggregate and deploy as self-built, habitable infrastructure. The study focused on the relationship between material resonance, earthquake-resistant structures, and fabrication strategies.

An agent-based form-finding algorithm was developed using knowledge acquired through physical prototyping of mycelium-based composites to generate earthquake resistant geometries, optimize material usage, and enhance spatial performance. The results show compelling evidence for a construction methodology to design and construct a 3-4 story building that holds a higher degree of resistance to earthquakes. The scope of work contributes to advancements in bioengineering, confirming easy-to-grow, light-weight mycelium-composites as viable structural materials for construction.
INTRODUCTION
On 25 April 2015, nearly 9,000 people were killed in a devastating 7.8-magnitude earthquake in Nepal. As a result, over 1,200 adobe buildings in the heart of the Kathmandu Valley were completely destroyed (Figure 1). The damage cost the country an estimated 10 billion dollars, where the government offered homeowners $3,000 each to rebuild their homes. Unfortunately, the figure only covered a quarter of the cost of rebuilding a typical family dwelling, leaving many Nepalese without a place to live (He et al. 2018).

Three years later, and despite the devastating impact of the earthquake on the urban fabric, builders continue to utilise outdated and inefficient construction techniques. Hence, the desire for inexpensive, self-built infrastructure is drastically growing (Daly et al. 2017). Previous research suggests lowering construction cost is through using locally sourced biomaterials (Peters 2015). However, although low-cost, little attention has been paid to using biomaterials for earthquake-resistant structures.

The research presents a state-of-the-art construction process that allows victims affected by large magnitude earthquakes to grow and assemble earthquake-resistant homes. By using strategies to dissipate seismic energy while maintaining and improving the efficiency of spatial relationships in Nepalese architecture, the presented research proposes a novel approach for the design and construction of a 3-4 story building.

Given the persistent seismic risks in the valley, there is a need to create a coherent regional structure for disaster recovery. Investing financial resources into housing without addressing people’s ability to re-establish productive lives, ensures they remain susceptible to future natural disasters. Therefore, recovery strategies need to strengthen local capacity for redevelopment in affected areas (Daly et al. 2017).

BACKGROUND
Earthquake Resistant Strategies
The three most relevant characteristics of an earthquake to consider while designing a structure are,1. The value of peak ground acceleration, 2. The duration of strong shaking, and 3. The frequency content of shaking. By altering the materiality, weight, design, and construction quality of a building, the behavior of a building can be designed to better withstand natural disasters (Galetzka 2015). Furthermore, there are three main design strategies that help to achieve earthquake resistance yet maintain cost efficiency: (1.) increase the structures’ stiffness to a point where its natural frequency is beyond the frequency of an earthquake, (2.) use mechanical methods to dissipate earthquake energy, and (3.) increase the structures’ flexibility to dissipate the energy before structural failure.

Trees In Nature
To address the points above, natural systems; specifically the structural characteristics of trees, provide an excellent resource. Trees in nature remain undisturbed during seismic events (Hanns-Cristof et al. 2013). Like buildings,
trees are subjected to resonance induced harmonic motion under the influence of wind or seismic forces. Research on different tree species suggests that oscillation damping accounts for their ability to withstand strong periodic wind loads. Mechanical energy imposed by gusty winds can be either converted to heat by viscous damping in the material or it can be dissipated to the surrounding fluid (air) (Hanns-Cristof et al. 2013).

As frequency bands overlap within branches a phenomenon known as resonance energy transfer distributes mechanical energy over the entire tree (Figure 2). Such that, the energy is dissipated efficiently by engaging more branches reducing the risk of failure associated with high energy concentration. Moreover, hierarchical differentiation subdivides the forces affecting the tree by generating multiple mass dampers, known as damping by branching.

The two features of modal dynamics on trees that may be applied at the building scale for earthquake resistance are 1. Modal frequencies of each branched hierarchy are relatively close together and 2. The resulting modal shape corresponds to each hierarchy (Kenneth 2006).

Mycelium-Based Composites
Coupled with the structural approach explained in the previous section, materials derived from biological resources can lead to create low-cost, sustainable building materials for construction. Polymeric materials, such as cellulose, lignin, pectin, and fungus are biocompatible and biodegradable with a wide variety of properties. Previous research has suggested that mycelium can be tuned during the growth process. Not only does utilizing fungal growth to create bio-material composites make production ecological, where building debris is lightweight and biodegradable, but also the materials’ innate resonant properties allow for effective energy dissipation during seismic events (Mitchell 2017).

Mycelium is the vegetative lower part of fungi, where the growth process prior to the production of mushroom results in a hard sponge-like material that has a high strength to weight ratio (Du et al. 2016) (Figure 3). It grows in a symbiotic relationship with the materials that feed it, forming entangled networks of branching fibers.

Mycelium based composites can be directly used to replace plastic and oil-based materials and have been currently used to create foam-like packaging, reinforce lightweight masonry structures, and furniture. Mycelium composites may be grown using a variety of locally available mushroom spores as well as substrates making them an infinitely renewable resource (Du et al. 2018). Moreover, the actual production of the material requires basic knowledge and setup of a sterilised growing environment, easily learned by unskilled home-owners (Daly et al. 2017) (Figure 4).

As mycelium is made up of numerous branching hyphae, a dense physical matrix of hard foam-like consistency is created. Research conducted at Utrecht University and the material lab at Delft University of Technology in the Netherlands advised that substrates that are harder to
digest such as hardwoods, result in harder composites with relatively higher compressive strength when compared to substrates easier to digest; it may be possible to engineer mycelium-based materials that have anisotropic physical properties within a homogenous fabrication system (Haneef et al. 2017). For example, The Hy-fi Tower (2014) at Moma PS1 in New York City was a 4-story circular tower structure made up of organic mycelium bricks and reflective plastic bricks. The organic bricks were produced through a combination of corn stalks and a specially developed mycelium composite by Ecovative Design. The reflective bricks are used as growing trays for the organic bricks, and then incorporated into the final construction before being shipped for reuse. This ‘low-tech biotech’ approach offers a new vision for built infrastructure and redefines the use of local materials (Peters 2015) (Figure 5). Netherlands advised that substrates that are harder to digest such as hardwoods, result in harder composites with relatively higher compressive strength when compared to substrates easier to digest.

Material Properties
Previous research has proven the structural resilience and real-life applicability of mycelium-based composites. The research focused on visual appearance, density, mechanical properties, and water-absorbing behavior (Figure 6). It was observed that ‘formation by pressing’, impacted the tensile strength and elasticity modulus of mycelium-based materials. Tensile strength and elasticity modulus of heat-pressed materials were higher when compared to the corresponding cold-pressed and non-pressed materials.

The high degradation temperature and moisture exposure suggests mycelium as an efficient building bio-material (Figure 7) (Karana et al. 2018).

METHODS
The aim of the research presented is to achieve earthquake resilient behavior using a mycelium-composite material and manipulating the structure’s geometry. Branching is used as a guiding principle to dissipate energy on a 3-4 story structure. In the event of resonance induced harmonic motion in a tree, kinetic energy is transferred through discrete hierarchical elements subdividing the energy at each successive node. Friction due to oscillation of branched elements releases heat to further dissipate energy. Altering the number, size, and mass of branches can affect the rate and magnitude at which energy is dissipated (Rodriguez et al. 2008). Further, material is strategically removed to minimize the amount of mycelium needed to grow and construct the proposed building. Hence, the objective is to minimize the mass of the structure while maintaining the structural integrity of the building.

Branching Principles
Earthquakes are expected to occur within a frequency range of 1 to 6 Hz. For branching to dissipate energy efficiently, it is ideal that as many modes as possible of a structure fall within this frequency range.
Figure 8 demonstrates how changing branch number, size, mass, and symmetry result in higher hierarchical differentiation, lowering modal frequencies and increasing proximity between modal shapes. To simulate the effect of branching on a 1:1 scale building, a simplified digital model using mycelial properties is produced with CAD software. Building dimensions represent the correct height and internal distribution of a mid-rise building. Three branching scenarios are defined by varying the number, height and symmetry of the branches (Figure 8).

Prior to experimentation a natural frequency analysis is performed to establish a baseline. It is then performed on all iterations to compare frequencies at which the first ten modal shapes occur using FEA software, Strand7. The iteration with lowest modal frequencies and lowest relative difference between frequencies is selected and used to inform the design proposal (Figure 11).

The spatial implications of branching are to be considered both in terms of programmatic arrangement and relative displacement. Branching morphologies with high performance are solutions with high displacement, making the building uninhabitable. Moreover, excessive branching may result in inefficient use of land and horizontal programmatic discontinuity. Therefore, a balance between branching performance and programmatic logic must be established.

Agent Based Optimization
Earthquakes are expected to occur within a frequency range of 1 to 6 Hz. For branching to dissipate energy efficiently, it is ideal that as many modes as possible of a structure fall within this frequency range.

In addition to utilizing a branched global geometry, reducing the mass of a structure will further increase earthquake resistance. The primary objective of the proposed form-finding method is to reduce material utilization through systems that respond to structural and spatial constraints (Figure 10). Reflecting upon mycelium growth patterns and naturally occurring branching morphologies previously discussed, a form-finding system that results in emergent global patterns through discrete local interactions is explored (Pantazis et al. 2017).

“Swarm intelligence describes the behavior exerted by natural or artificial self-organized systems, which are made up of boids/agents interacting locally with one other and their environment. These interactions lead to the emergence of complex systems demonstrating intelligent behavior on a global level” (Pantazis et al. 2017).

The generative morphologies of agent paths are used to inform locations where material is added or removed on the base geometry. By analyzing the structure and spatial implications posed by the proposed agent-based model, a feedback loop is created between computational design, digital fabrication, and material research.

The initial experiments were carried out on a simplified geometry to compensate for computational limitations. The
system aims to minimize material usage and maximize structural performance to create a homogeneous and continuous geometry using CAD based meshing (Figure 12). Fabrication and material constraints inform meshing parameters. A comparative analysis of the resulting geometry against the baseline geometry is conducted to quantify the percentage difference in volume while retaining structural performance. The final model is developed using Quelea and Culebra. FEA is conducted using Karamba 3D in the Rhino/Grasshopper environment and results are verified in Strand7 (Figure 9).

Structural and solar analysis coupled with flocking parameters describe the bottom-up approach to generating locally optimized and globally emergent patterns, where the base geometry used for the agent based-system describes the top-down approach.

Solar radiation analysis using Ladybug is carried out on the façade of the building on December 21 from 6am to 6pm to determine incoming radiation at the lowest sun angle that occur during the winter months. Repeller obstacles are placed to create openings that correspond to those data points to maximize internal solar exposure. Force flow lines obtained from FEA of the base geometry are used as guiding paths for the agent; the repeller force and multi-path follow force remain constant while agent number, cohesion, separation, alignment, and vision radius are varied iteratively (Figure 13).

The agent paths describe areas on the walls where material is fully present and the resulting mesh displays a maximum thickness value defined by fabrication and material constraints. Experimentation is carried out in two steps: First, agent paths are meshed and joined with the floor slabs, with no walls present, to establish a minimum material usage condition. Then the model is analyzed to ensure adequate structural performance. In the second step agent paths are overlaid on the base geometry and the combined mesh is thinned incrementally towards a defined minimum. The model is analyzed to ensure that material usage is reduced but retains structural performance. By overlaying the agent paths on the base geometry, the combined mesh is thinned out incrementally to achieve a buildable thickness. The distances between the mesh points and agent paths are multipliers for the incremental thinning process and openings begin to emerge as points are moved beyond the minimum thickness. The resulting solution lies between the geometry described by the agent paths and the input form. Though the performance of the system is verified through FEA, it is important to further develop the research towards physical prototyping and testing to verify...
the performance of the proposed construction system.

**Agent Based Optimization**

The primary objective for this experiment is to optimize material usage as a part of the design process. By intelligent removal of material from the structure it is possible to decrease the building mass while retaining structural performance, thereby increasing earthquake resilience. This hypothesis is tested by comparing the material volume and maximum displacement of the initial and resultant geometries.

The first set of experiments are carried out on both the exterior and interior wall subsystem of the building to generate a reduced structure and produce the inputs required for further investigation. FEA of the initial geometry results in force flow lines which are used as input curves for the multi-path follow force. Through a solar radiation analysis, repeller points are determined based on where openings are required. This is done iteratively by varying the flocking parameters as well as the density of agents while maintaining a constant initial geometry along with its structural and environmental inputs. The marching cubes algorithm is used to generate 3D geometries from the agent paths. Nine iterations are run through FEA and the resulting displacement and volumes are compared to define settings and configurations that will be carried forward for the proposal (Figure 14).

An initial geometry is setup as a 9 x 9 x 18 m building with internal partitions generating four rooms on each floor. This is done to define a simplified geometry which is representative of the proposed architectural scale while allowing for the experimental process to be tested quickly before applying the result to the final geometry. The wall thicknesses are set to 500 mm, the dimensions derived from local adobe construction. Through an initial FEA using Karamba3D, force flow lines are generated, and the maximum displacement of the base geometry is defined as 0.1m. Support points are defined on the ground plane and the physical properties for the mycelium composite are used to run the simulation (Figure 15).

Ladybug is then used to generate a solar radiation map on the façade of the structure to determine where repeller points are needed to create openings on a building; the number of repeller points directly correlate to the size of fenestration required. Solar radiation is analyzed on the 21st of December for a 12-hour period during the day, where areas least exposed to the sun are given more repeller points.

Agents are emitted from the ground plane perimeter of the building and are programmed with a Z-direction bias. This is done to generate a vertical structure that is denser closer to the ground and becomes lighter as height increases. The flocking parameters of cohesion, separation, alignment, and vision angle are varied across the iterations to analyze their impact on the resulting structure. Initial experiments (see Figure 16) concluded that 150 timesteps are needed to generate agent trails that extend the height of the building.
RESULTS

Three sets of experiments using 30, 40, and 50 agents, respectively were tested to study the effect of flocking behavior on self-organization (Figure 17). In the first set of iterations 5.3.1 (Figure 20), a bias towards alignment with moderate vision radius result in consolidated agent paths that appear to be highly responsive to repeller obstacles, producing defined openings on the building surface. The iterations with high cohesion and low vision radius 5.3.2 display similar behavior, with increased interconnectivity resulting in locally branched morphologies. And finally, iterations with high separation and high vision radius 5.3.3 (Figure 20) display significantly more interconnected agent paths. Based on branching principles, the likelihood of interconnected agents increasing earthquake resistance is high.

The displacement values obtained from FEA indicate that the resultant structures undergo a maximum displacement of 0.177m (5.3.1b) and minimum displacement of 0.059m (5.3.2c) across all iterations. Comparing the volume to the initial geometry (921 m³), all iterations display reduced material volume by 40-53%. In the iterations with high alignment and cohesion, the number of agents is directly proportional to the volume and inversely proportional to maximum displacement. However, this trend does not apply to iterations with high separation, where the individual with 40 agents minimized displacement having lower volume than the individual with 50 agents. It appears that iterations with 40 agents are most favorable in terms of material reduction and locally branched morphologies.

Out of the 9 iterations, 6 display a maximum displacement of 0.1m or less. 5.3.2b (Figure 20) has the lowest displacement to volume ratio with a maximum displacement of 0.059m and volume of 731 m³. It achieved a 20% material reduction compared to the baseline model.

The resulting geometries are analyzed through FEA to determine the maximum displacement and stress per brick, and is compared to the modified values for material volume. In this experiment, although the designer has complete control over the resulting wall thicknesses, the shapes of the openings are directly derived from the previously generated agent paths. By incrementally reducing the walls, the designer is able to control the steepness of curvature obtained between the ‘structural veins’ described by the agent paths and ‘reduced walls’ created through this process. The amount of curvature has direct implications on the fabrication constraints, thus playing an important role in the global design process.
Experiments to determine the least amount of material needed for structural performance

Figure 21 shows that as the mesh is thinned, the volume of the structure reduces by almost 80 m³ across all iterations. Although the resulting displacement and stress/brick values negligibly vary, displacement decreases with volume as the structure becomes lighter despite an increase in stress/brick. 5.4a has the maximum volume (417 m³) and exhibits the maximum value for displacement (0.29 m) and minimum value for stress/brick (0.26 MPa). 5.4d has the minimum volume (333 m³) and exhibits the minimum value for displacement (0.26 m) and maximum stress/brick (0.362 MPa). It appears that the displacement and stress values are similar between first and last two iterations, with a relatively large jump in values between 5.4b and 5.4c. This may suggest a critical threshold for the material in terms of structural performance and volume.

Reflecting on all 4 iterations, 5.4c (Figure 21) exhibits the lowest value for displacement (0.268 m) under self-weight with a decrease in material volume by 11% when compared to the baseline volume of 921 m³. The minimum
wall thickness in this iteration range between 0.15 m to 0.2 m, with a maximum of 0.52 m (within the constraints of the fabrication and material properties). It is observed that areas with resulting wall thickness of 0.15 m largely coincide with the position of repeller points. The density of points that are 0.15 m from the inner surface increases with height, making it possible to create larger or increased window openings on the higher floors.

Experiments 5.3 and 5.4 (Figure 20, 21) both aid in creating a computational framework for generating structural geometry from agent paths. As the initial goal of the agents was to optimize material usage in terms of structural performance, experiments 5.4 carry forward the results of 5.3 by introducing the possibility of non-generative architectural detailing. Hence, this becomes an important step for synthesizing architectural morphologies from abstract computational models. However, future study should test this experimental process on complex base geometries. As the complexity of the base geometry increases, it is challenging to separate internal and external surface points. Nonetheless, these set of experiments offer the designer to edit, assess, and design the building system, which up to this point in the research has been created through computational generative processes; an interesting opportunity to explore the role of a designer and his/her impact on a data-driven generative design system.

ANALYSIS
The results obtained in agent-based form finding, agent-based material optimisation, and branching experiments, help to simulate the structural implications of the building system. The computational limitations of the FEA software allowed for experimentation to occur on simplified geometries, where the results are used to inform the final design. The global objectives of reducing material while maintaining structural performance and reducing the range and relative difference of modal frequencies are the drivers for every step. Figure 22 shows the synthesized application of the last four experiments. The iteratively selected settings for the agent-based material optimisation applied to the selected branched morphology. Namely, high density, high separation and high vision radius settings from 5.3.2bc (Figure 20) and asymmetrical branching morphology are combined to reduce wall thickness by up to 0.3 meters.

Two building geometries are compared through FEA, with and without openings, to test displacement, stress, and natural frequency. The relative changes in modal frequencies are compared to the baseline geometry generated prior to agent-based material optimisation.

Figure 22 shows modal frequency values for 3 selected geometries. The baseline geometry has the lowest modal frequency out of the three, however, the difference between the baseline geometry and the geometry without openings are negligible. Therefore, the focus shifts to the geometry with openings. The graph shows a drastic change between modes 5 and 6, versus a mild change between modes 8 and 9. As previous research has shown, the change in frequencies within the modes of a geometry occurs due to the

19 Comparative analysis; displacement (cm) and volume (m3) for each iteration
21 Obtained results after material removal
22 Synthesized application of experiments 5.3 – 5.6 combining agent-based form finding, agent-based material optimization, and branching.
The hierarchical nature of the branched morphologies. As the modal number increases, branches higher up in the hierarchy oscillate and a shift occurs whenever subsequent branch is excited. It is evident that there is a direct correlation to the dimensional hierarchy of the branches and the number of modes at which harmonic motion is induced; larger branches correlates to the lower modes, number of mode increases as branch size decreases.

Therefore, it is likely the shift in frequency between modes is gradual when modulating the sizes of the building branches to incrementally decrease with height. It is observed that the displacement and stress values between the geometries with and without openings negligibly vary, however, a significant decrease in volume by 15% shows this method is structurally feasible and optimizes material usage.

CONCLUSION
The 2015 Nepal earthquake has displaced over 6.6 million lives in the Kathmandu valley where 600,000 homes were destroyed, largely due to outdated construction methods using adobe bricks. Kathmandu’s density coupled with high rates of pollution has increased the demand for inexpensive, self-built infrastructure that is both earthquake-resistant and ecologically produced. However, the local government has done little to find a balanced solution.

This research designed and proposed an earthquake-resistant building that uses mycelium-composites as locally-sourced building alternatives. We tested building geometries that increase earthquake resistance, optimize material usage, and enhance spatial occupation for displaced peoples to reconstruct their homes.

We found that 3-4 story globally branched building structures, grown of mycelium, do, in fact, increase earthquake resistance. By generating an agent-based form-finding algorithm with knowledge acquired through physical prototyping, this research offers an ecological construction methodology.

The scope of work contributes to advancements in bioengineering, confirming easy-to-grow, light-weight mycelium-composites as viable structural materials for construction. Experiments show that the building geometry has more influence on structural performance than the material properties. The study therefore indicates that the benefits gained from agent-based simulations address earthquake-resistance.

Our results provide compelling evidence for a methodology to design and construct a 3-4-story building and suggest that this approach is effective for communities that are susceptible to natural disasters. However, some limitations are worth noting. Although we were able to grow 1:1 mycelium samples to produce curvature generated by agent-based simulations, the growth process is inconsistent making it difficult to physically test the material for architectural application. Future work should therefore address engineering a mycelium-composite for complex homogeneous structures that shift the industry standard for earthquake-resistant buildings.

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REFERENCES


**IMAGE CREDITS**

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