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ANALYZING THE IMPACT OF THE ASPECT RATIO OF A BUILDING ON CONCRETE USE IN ITS STRUCTURE

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Abstract. Buildings consume over half of annual energy supply as embodied and operating energy in their construction and operation releasing harmful emissions to the atmosphere. Over 90% of the embodied energy is attributed to construction materials used in building structure, envelope, and interiors that must be reduced to minimize material use. Concrete is one of the major materials that contributes significantly to the energy and carbon footprint of buildings, as it is responsible for 5-9% of global carbon emission. Because most of the concrete use in the building sector occurs in building structures, assessing how building design parameters influence its environmental sustainability is important. One of the design parameters that impact the sustainability of buildings is the aspect ratio, which is defined as the ratio of horizontal to vertical surface area of a building. A building with the same floor area can be designed horizontally or vertically with different aspect ratios, which will influence its structural design and eventually the amount of concrete used in the building. In this paper, we examine how aspect ratio may affect the environmental sustainability of a buildings foundation, structural framing, and slab. We model the structure of a generic building with different aspect ratio to analyze if aspect ratio can help reduce the energy and carbon embodied in reinforced concrete structures.

Keywords: Aspect ratio, concrete, embodied carbon, embodied energy, environmental sustainability.

1. Introduction

Building sector consumes nearly half of global energy supply in building construction, operation, and maintenance as embodied and operating energy, releasing over 40% global carbon emission [1, 2]. For an effective reduction in a building's energy and environmental footprints for long-term environmental sustainability, the use of both embodied and operating energy must be minimized [1]. With emerging advanced materials, energy-efficient technologies, and regulations, the operating energy use is decreasing gradually [3]. However, to reduce embodied energy, the use of energy intensive materials must be controlled [2]. Over 90% of a building's embodied energy can be attributed to construction materials [2]. This means that the greatest opportunity to minimize embodied energy impact lies within construction material domain. One such material is concrete, the use of which has always been extensive and would continue to grow realizing its mechanical strength as well as durability [4–6]. It is the most consumed solid material in the world by mass [4, 7] and is also a material of choice for emerging construction automation technologies such as 3D-printed or additive construction, which are garnering the attention of the construction sector due to their higher productivity, efficiency, and safety [6]. However, concrete is also responsible for 5-9% of global carbon emission, primarily due to the use of cement [8–10]. Roughly 74%-81% of the total carbon dioxide emission from concrete production comes from Portland cement use with just 13%-20% originating from coarse aggregates [11]. Several studies have been targeting concrete to enhance its environmental sustainability [11]. However, effectively reducing its energy and carbon footprint is still challenging [4]. There are two approaches to advance the sustainability of concrete, particularly in the construction sector. The first approach involves material science to either modify or replace cement, the main ingredient responsible for a majority of carbon emission of concrete [4, 11]. The second approach is to minimize the use of concrete through design so that it is consumed only in components that actually need its mechanical properties and durability [6]. In this paper, we analyse one of the design parameters, the aspect ratio of buildings, to understand how the use of reinforced cement concrete is affected by the aspect ratio.

2. Concrete Sustainability

Among the widely applied approaches to enhance the environmental sustainability of concrete is replacing or reducing the amount of cement use in a concrete mix [11, 12]. Reducing cement quantity by adding pozzolanic materials such as fly ash, silica fumes, natural pozzolans, rice-husk/wood ash, or granulated blast furnace slag (GBFS) is one example of minimizing the carbon footprint (13%-15% reduction in CO2 emission) [4, 7, 11, 12]. Likewise, fiber-reinforced concrete (FRC) is another example to enhance the overall sustainability of concrete through reduced construction time (37% decrease) and cost (12% decrease) as well [5]. Studies also used inorganic polymers or geopolymers as well as calcined clays to supplement cement in concrete [4]. Using recycled concrete aggregate (RCA) has also been examined to lower the adverse environmental impacts of concrete [12]. The manufacturing process of cement (dry vs. wet process) as well as the type of fuel consumed is also being targeted to capitalize on any opportunities of saving energy [7, 12]. The other approach to improve the environmental performance of concrete involves design of concrete mixes for higher durability and strength and lower maintenance requirements so that the amount of concrete over a structure's life cycle can be reduced [4, 12]. By modifying the packing factor, size, and shape of aggregates and controlling the amount of water, concrete mixes can be optimized for smaller carbon footprints. The use of concrete can also be optimized through innovative automated construction processes as well as designing a building or a structure in ways that boosts the material efficiency to decrease concrete use [6]. One of the building design parameters is the aspect ratio that has been studied by several studies for not just operating and embodied energy usage (heating and cooling loads) but structural optimization as well [13–16]. Most studies defined aspect ratio as the ratio of the width (or depth) and the height of a building that influences structural behaviour under normal load conditions as well as wind loads [15]. Some studies (e.g. [16]) revealed that aspect ratio can significantly influence the quantity of construction materials as well, affecting overall embodied energy and carbon emission. In this study, we conducted a preliminary analysis of how aspect ratio influences the amount of concrete and steel in a building's structure. The goal is to examine whether tall or horizontal buildings help enhance the sustainability of concrete as a construction material.

3. Research Goal and Methodology

The primary objective of the present research is to assess the impact of aspect ratio on the use of concrete in buildings. The following are the key objectives of the research paper:

3.1. Objective

1. Define aspect ratio as surface aspect ratio which is the ratio of the horizontal (floor) surface area to the total vertical (peripheral) surface area.
2. Calculate the quantity of steel and concrete required for buildings with different aspect ratios.
3. Compare the results for different aspect ratio cases and discuss the impact of the variation in material quantities.

3.2. Approach

3.2.1. Defining surface aspect ratio (AR_s)

In this paper, the surface aspect ratio (AR_s) of a building is defined as the ratio of the total area of the horizontal and the vertical surfaces of a building. The aim is to understand the relationship between surface aspect ratio and the quantity of materials (concrete and rebar steel) used in the structure of a building. This was achieved by conducting a structural analysis of a 12-storied commercial building. The surface aspect ratio of the building was incrementally changed to investigate its effect on the quantity of concrete and steel used in the building structure. This relationship is important to examine if a design parameter (AR_s) influences the amount of concrete and steel used in a building's structure, and eventually affects the sustainability of concrete. The total floor area of the commercial building is approximately 10,600 m^2. To obtain the average area per floor, for the given plan, the total area is divided by the number of floors, $N_f + 1$. The additional floor designates the reinforced concrete roof. The length and breadth are calculated from the average area per floor using the assumption that the length of the floor, L, is two times that of the breadth of the floor, b.

The surface aspect ratio is varied by changing the number floors from twelve to nine, six, three, and one. The total usable floor area of the entire building is maintained constant to make the comparison of steel and concrete usage. The average area per floor is calculated based on the different N_f values, which is eventually used to calculate length and breadth dimensions. Evidently, when the total floor area is held constant, the horizontal dimensions i.e., length and breadth of the building, are observed to increase with a decrease in the number of floors. The interior floor to ceiling height of each floor, h, is also held constant to 13 feet. In this study, horizontal surface refers to the individual floor surface and the vertical surface represents the exterior peripheral surface as shown in Figure 1. Here, we defined aspect ratio (AR_s) differently as the ratio of horizontal to vertical surface area. The horizontal surface area, H_a, is quantified using the length and the breadth of the floor plan. The vertical area, V_a, is calculated as the sum of the products of total building height and that of length and breadth. The surface aspect ratio of the building is computed as H_a/V_a. Assuming the thickness of the exterior wall assembly as 9 inches and slab thickness of 6 inches, the centre-to-centre dimensions of length (L_{clc}), breadth (b_{clc}), and height (h_{clc}) are calculated.

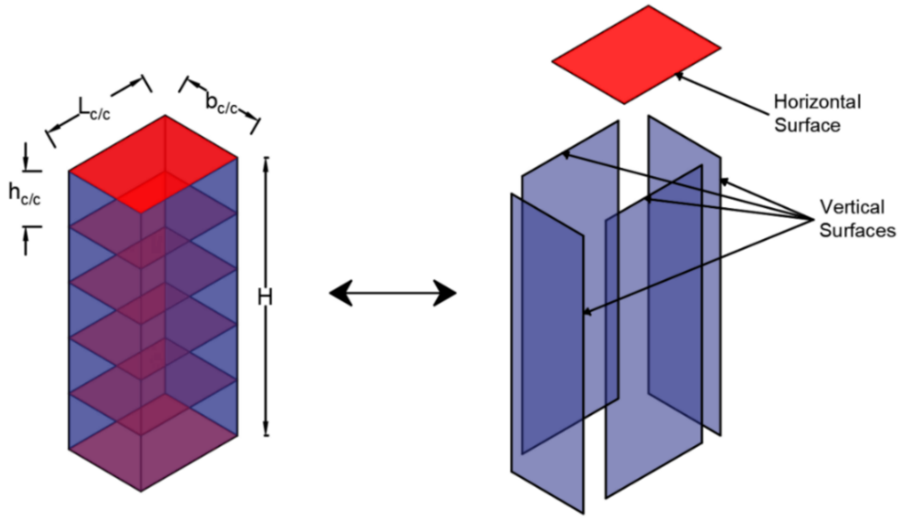

FIGURE 1. Horizontal and vertical surfaces of a building considered to define surface aspect ratio

Member Assignment		Material Assignment		Loading Assignment		
Parameters	Dimension [inches]	Parameters	Yield Strength [ksi]	Parameters		Load value
Wall	9	Concrete	4	Dead Load of Wall DL_{wall}		104 lb/ft
Slab	6	Rebar Steel	60	Live Load	Floor / Roof	100 psf 20 psf

TABLE 1. Structural Modeling Assumptions.

Number of Floors, N_f	12	9	6	3	1
Surface aspect Ratio	0.14	0.21	0.37	0.99	4.19

TABLE 2. Surface Aspect Ratio for Different Floors.

3.2.2. Structural Analysis and Quantification of Materials

To perform the structural analysis of floor plans with different surface aspect ratios, ETABS v18 structural software is used for the superstructure and Rapid Interactive Structural Analysis (RISA) Foundation is used for foundation/footing analysis. First, the structural model is prepared for each case of surface aspect ratio, by assigning horizontal and vertical structural members (reinforced concrete columns and beams) as well as 6-inch-thick slab. The dimensions of the beams and columns are fed to the autogenerated list in ETABS using the "auto-beam" and "auto-column" options. The standard beam and column dimensions are input in the list which the software uses to randomly assign to the respective beams and columns for the initial model before the analysis. Table 1 lists all the key assumptions used for structural modelling.

The loads are assigned based on the standard loading reference of ASCE7 [17]. The exterior wall assembly of 9 inches thickness is assumed to be non-load bearing, and their dead load is assumed as uniformly distributed along the wall location. The dead load of the walls of 104 pounds per linear foot (lb/ft) is assigned based on the assumption that a normal partition stud wall with 0.5 in. thick gypsum board on each side for a wall/floor height of 13 ft, as per C4.3.2, ASCE7. The floor live load of 100 pounds per square foot (psf) and roof live load of 20 psf, respectively, are assigned as per ASCE7. ASCE7 auto lateral load is assigned to define the wind load case. All parameters (exposure, wind pressure and co-efficient) are kept the same as the default values from ASCE7 in ETABS for this study. Application of wind lateral load from different direction and of different wind parameters is not accounted for in this study. The analysis is run, and the optimal design is generated using the list of standard beam and column dimensions. The quantity take-off is estimated from the software and the results are plotted between the surface aspect ratio and the amount of concrete and steel used for the buildings with different number of floors. The foundation is designed using the RISA Foundation software. The dimensional range of the foundations are also provided in a similar way explained previously for the beam and column design in ETABS. The dimensions ranged from a minimum of 2 ft to a maximum of 20 ft. Isolated footings are assumed as the type of founda-

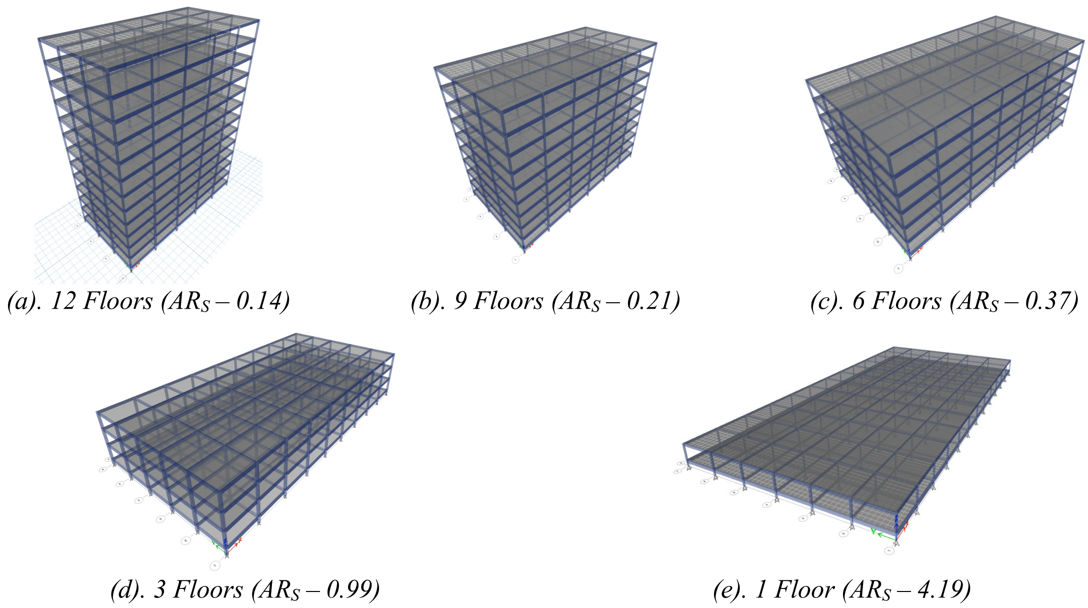

Figure 2. Different types of models prepared for surface aspect ratio analysis.

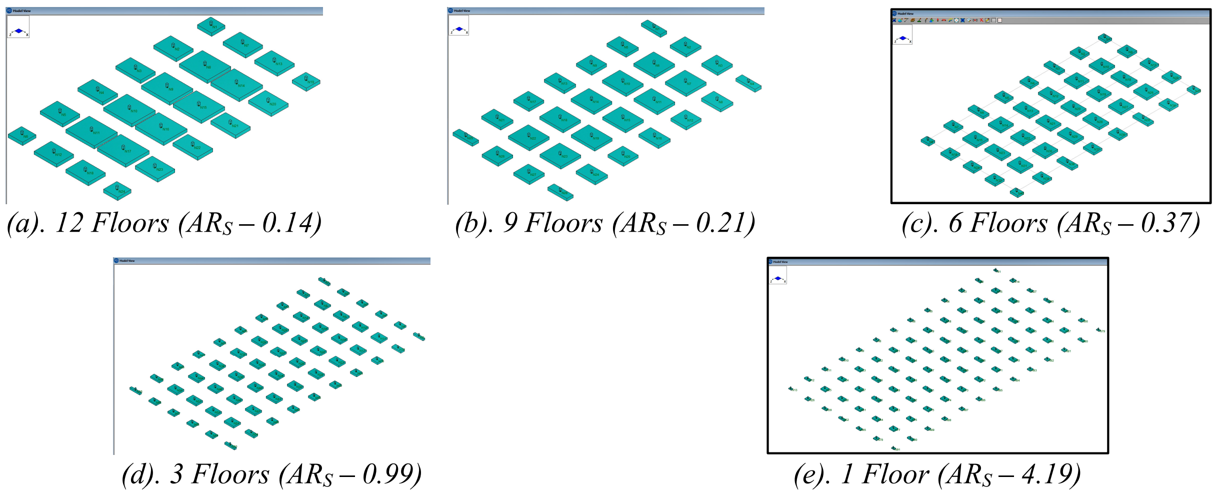

Figure 3. Isolated footing foundation models.

tion. The dead load and live load loads are assigned as point loads on the footings, using the base reactions of the superstructure analyzed and designed in ETABS.

4. Results

Table 2 lists different surface aspect ratios of the building considered in the structural modelling. Figure 2 shows building models with different surface aspect ratios. The structural analysis of these five building models was carried out individually using ETABS and RISA Foundation. As seen in Figure 2, the horizontal floor size increases with the decreasing surface aspect ratio and increasing total height of the building, keeping the total usable floor space constant. Figure 3 shows the foundation detailing for all five structural models. Figure 4 illustrates the relationship between different surface aspect ratios and the quantity of steel and concrete used in building structures. The quantity take-off for each case is plotted against the respective surface aspect ratio. The surface aspect ratio is plotted on a log normal scale on the X-axis. The two materials whose quantities are plotted on the Y-axis are steel and concrete.

From the plot between the quantities of steel and concrete versus surface aspect ratios, the impact of surface aspect ratio on material quantities can be understood. The quantities of the construction materials decrease as the surface aspect ratio increases. The rate of decrease is higher for steel usage than the concrete. Thus, the quantities of steel and concrete for a unit vary inversely with the surface aspect ratio raised to some exponent greater than unity. The quantities of steel and concrete are also compared with the number of floors in the unit. The number floors are also plotted on a log normal scale as the secondary X-axis as shown in Figure 4. The quantities of steel and concrete increase with the increasing number of floors.

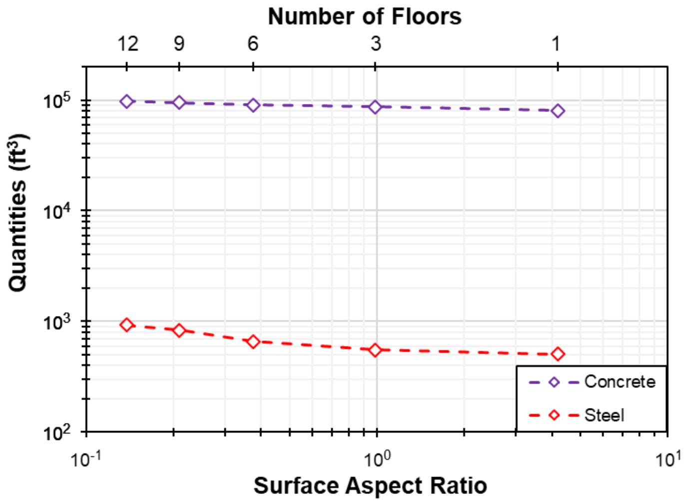

FIGURE 4. Relation between quantities of concrete and rebar steel.

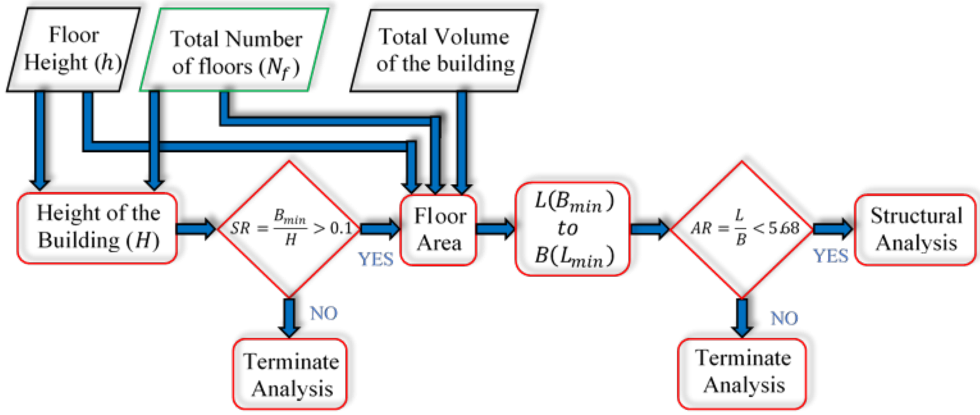

FIGURE 5. Flow chart for determining the boundary limits to carry out further structural analysis.

It may be structurally justified that as the height of the structure increases, the total gravity load onto the base columns increases, increasing the base reaction. This raises the quantity of steel and concrete required for individual footing. Further, as the loads are higher on columns at the bottom level of tall buildings, the size of columns and beams goes up from top to bottom of the building, which tends to increase the total volume and quantity of materials required for each structural component. However, slab volume and material quantity remain approximately the same as the total floor area and slab thickness are kept constant. The drop in quantity of concrete and steel is, therefore, directly dependent on the total load transferred to each structural member. The results clearly show a decrease in the quantity of steel and concrete as the surface aspect ratio increases. This relates to the carbon footprint of the structure. It can be concluded that, the surface aspect ratio of the building may be judiciously used to ensure that the building construction is sustainable, while maintaining the utility of the unit. This can be achieved by choosing a reasonable combination that satisfies a minimum quantity of raw material consumption while maximizing the services desired from the building space and dimensions. This study shows that the surface aspect ratio can be a good tool in the planning of buildings with the objective of reducing the carbon footprint of the project, particularly in the construction stage because this analysis can lead to huge saving on the construction material by the selection of an optimum surface aspect ratio.

5. DISCUSSION

From the results presented in the previous section, one may see that for the five cases of different surface aspect ratios, the total quantity of steel and concrete decreases with an increase in the surface aspect ratio. However, these results are based on just a preliminary analysis of the five cases. To improve the efficacy of the model to make robust conclusions on the impact of aspect ratio, a more rigorous structural analysis needs to be carried out that considers not just several aspect ratios but different building orientations as well. We are currently in the process of programming a code to run exhaustive structural simulations, which include a wide range of building orientation, floor size variations, and aspect ratios. Two primary inputs are considered: (a) the total usable volume of the building (V), which is held constant throughout the analysis and is calculated using an existing 12 storied building plan, and (b) the total number of floors in the building (N_f), which is varied starting with one floor. As seen in Figure 5, the simulation begins with the number of floor (N_f) as one and using the floor height (h) computes the total height of the building. The number of floor (N_f) is then increased incrementally, quantifying the corresponding total height of the building. For this study, only non-slender buildings are considered by performing a check of slenderness ratio (SR). The slenderness ratio (SR) is defined as the ratio of the smallest horizontal dimension and the height of a building (H). Fu [18] suggests that most structural engineers consider buildings with $SR < 0.1$ to be slender. This parameter gives the maximum number of floors that may be considered for analysis. Using V and N_f, the total area per floor for each case is calculated, which is eventually used to estimate the length and breadth of the building. To ensure that either of the length and the breadth of the building is not too narrow to render the building non-functional, we will use single or double-loaded corridor/hallway configuration to derive a minimum dimension. This minimum dimension will control the least length (L_{min}) and breadth (B_{min}) of the building that could be considered in the simulation. These dimensions are then used to calculate the ratio of the length and breadth of the building. Several studies (e.g. [19, 20]) suggest that buildings with the length and breadth ratio of 5.68 are the most economical in terms of energy costs as well as the quantity and quality of daylight. Therefore, the cases with the length and breadth ratio 5.68 will be excluded from the analysis. The cases that pass all the initial checks will undergo structural modelling including lateral load analysis along with gravity loads. The main parameters considered here are variation in spatial dimensions (length, breadth, and height of the building) and change in the orientation of the building to face the predominant wind direction. Geographic location parameters such as wind direction and speed and soil conditions are held constant. The goal is to evaluate the quantity of steel and concrete under different spatial and lateral load conditions to study the influence of aspect ratio on quantity of materials and the subsequent effect on the carbon footprint.

Even though the preliminary results suggest that the construction of taller buildings may need more quantities of steel and concrete than the horizontal ones, the sustainability of concrete should be viewed from a more holistic perspective that also includes other factors such as availability of land, land use and the area of impermeable surfaces on ground. For instance, a horizontal design of a building may help improve the sustainability of concrete through material savings, it may also intensify the urban heat island effect. In fact, horizontally designed buildings may also decrease ground permeability increasing the probability of flash floods, which is particularly concerning in the cases of radically changing climate. The amount of roof and wall surface also influences the amounts of heating and cooling loads of a building, which consequently affects the operating energy consumption. However, availability of land area for horizontal construction is a challenge and may call for vertical construction. Taller buildings, on the other hand, offer opportunities of having more permeable and green space on ground that may not just help control the urban heat island effect to keep the urban air temperatures low but also offer vegetated ground to soak rainwater and reduce the chances of flash floods. Increased green space may also mean enhanced quality of life as well as reinforced biodiversity through expanded natural habitat for different plant and animal species. Note that this paper is not favouring a tall building over a horizontal one. It is rather arguing to apply a holistic perspective to analyse the sustainability of concrete as it relates to individual building design as well as urban environments.

6. Conclusions

This paper presented preliminary findings based on the structural modelling of five different aspect ratios to compute the amount of concrete and steel used in the buildings' structure. The results showed that the quantities of concrete and steel increase with a decrease in the surface aspect ratio. In other words, designing a building vertically may require more material usage in its structure than a horizontal one. As these results are preliminary, we are currently developing a code to structurally analyze multiple combinations of the length, width, and height of a building model in different orientations to arrive at robust conclusions. Our goal is to examine if a design parameter such as the surface aspect ratio impacts the quantities of concrete and steel, and eventually resulting environmental impacts. We also argue that analysing the sustainability of concrete based on just material quantities may lead to misleading conclusions, as other environmental phenomena such as urban heat island effect, expanding land use, and flash flood events may need to be included in the analysis of the sustainability of concrete.

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