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Comparison of embodied energy and environmental impact of alternative materials used in reticulated dome construction

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ABSTRACT

The reticulated dome structure is a system composed of linear elements arranged in such a way that the forces are transferred in a three-dimensional manner. These dome structures require less amount of materials to be built when compared to continuous surface domes, thereby, reducing the embodied energy of the structure, i.e., the energy used in the manufacture and transportation of materials. However, selecting materials with high embodied energy can significantly impact the energy use and environmental impact of reticulated domes. In line with sustainable construction practices, use of materials that reduces overall embodied energy of the structure is desirable. This paper compares the embodied energy and related environmental impacts of four alternative materials used to construct these structures namely aluminum, steel, laminated veneer lumber, and laminated bamboo. To estimate the quantities required to construct the dome structure, a finite element-based structural analysis software, MSC Patran/Nastran was used. Using the estimated quantities of alternative materials, detailed life cycle inventory was performed using GaBi software. The results of the environmental impact assessment show that aluminum and steel have higher embodied energy when compared to the other two materials. Furthermore, the results show that bamboo has a negative global warming potential outperforming laminated veneer lumber option. Additionally, a simplified life cycle analysis tool, Athena Impact Estimator, was used to compare results obtained from GaBi analysis. Overall, the results indicate that the use of alternative materials can significantly reduce the embodied energy and provide environmentally sound options to address the current environmental challenges.

1. Introduction

Reticulated space structures deliver a widespread solution to provide incredible architectural designs without the constraint to maintain short span distances [1]. A reticulated structure is a system composed of linear elements arranged in such a way that the forces are transferred in a three-dimensional manner. Reticulated structures also referred to as space frames, are arranged in one, two, or multiple layers of intersecting members creating a curved surface termed as braced structures [2]. Fig. 1 shows a single and double layer frame arrangement, respectively.

Several space structures exist but the most common are domes, barrel, toroid and hypar as shown in Fig. 2 [4].

Reticulated braced structures differ from continuous surface vaulted structures primarily due to the relatively less amount of structural materials required to build them. However, domes are the oldest and well-established structural forms used in architecture since the earliest times due to their maximum amount of enclosed space with minimum surface [2]. Reticulated domes are commonly constructed of materials such as aluminum, steel, and wood structural elements [5].

Needless to say, the energy used and, thereby, their impact on the environment, in the manufacture and transportation of any product is an important factor to consider in the early stages of design. To this effect, Life Cycle Assessment (LCA) aids in the inventory and impact analysis to reduce the environmental impact associated with a product, process, or activity. This procedure considers the entire lifecycle of a product; the phases include extraction and processing of raw materials, manufacturing, transportation, distribution, use/reuse, recycling, and final disposal of the product after the end of useful life. LCA, as a tool, can be used to

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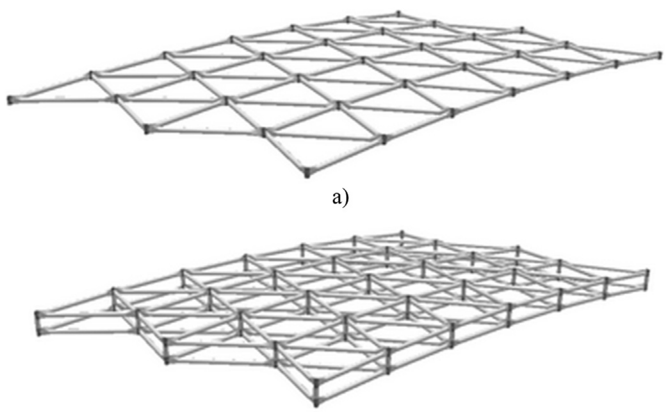

Fig. 1. a) Single layer frame, b) double layer frame [3].

identify the product that will potentially have the least environmental impact [6].

The construction industry, as a whole, uses large amounts of energy to extract an enormous amount of natural resources [7]. The energy required for raw material extraction, processing, and transportation of the final product to the construction site is the embodied energy of that product. In the LCA system boundary context, these collective phases are referred as a 'cradle-to-gate with transportation' [8]. Embodied energy does not include the operation and disposal of the building material at the end of its useful life. For the construction of any building, many processed materials are used, and each of them contributes to the total embodied energy. However, choices of different materials can considerably lower the amount of energy embodied in the constitution of the building. Although, in the past, it was believed that embodied energy of a building is insignificant as compared to the operational energy of the building, several research works [9,10] have shown that this is not always the case, particularly as in scenarios where embodied energy outgrew operational energy. According to Milne and Reardon [9], an average house contains about 1000 GJ of embodied energy in the materials used for the construction. Accordingly, embodied energy represents more than 10% of the energy used over its entire life of 100 years in low, normal, and high energy operation conditions.

Many studies have been conducted in the past to assess the energy performance of dome and vaulted roofs [11–13]. To date, a comprehensive embodied energy analysis of varied structural materials used in the construction of modern reticulated dome structures does not exist. Particularly, with the influx of new innovative designs of large-scale structures including indoor/outdoor sports stadiums, etc., the importance of identifying alternative materials in dome construction based on their embodied energy is crucial more than ever. This paper compares the embodied energy and related environmental impacts of four alternative materials used to construct these structures namely aluminum, steel, laminated veneer lumber, and laminated bamboo. The main objective of this study is to compare the embodied energy of alternative materials in a detailed and scientific manner. The results of this study are expected to positively impact the traditional design practices and decision-making process by providing a comprehensive embodied energy and environmental impact analysis and, thus, encourage the use of alternative materials not only for reticulated dome structures but also for other common types of frame structures. The paper is organized as follows: Section 2 reviews literature related to LCA, embodied energy, and alternative materials; Section 3 elaborates the four-step methodology to calculate the environmental impact of alternative materials used in reticulated dome construction, and this is followed by a discussion of results obtained from GaBi in Section 4. The latter part of Section 4 offers a comparison of GaBi results with Athena Impact Estimator.

2. Literature review

2.1. Life Cycle Assessment

Life Cycle Assessment is used to evaluate the environmental impacts of a product, process, or activity [6]. This process is composed of four components: goal and scope definition, inventory analysis, impact assessment, and interpretation. The goal and scope definition outlines the purpose, boundary conditions, and any assumptions made for the study. The inventory analysis or Life Cycle Inventory (LCI) quantifies the use of resources and energy in addition to the amount of releases to the environment associated with the system. Once LCI is quantified, an impact assessment is performed. In this stage, the results from the LCI are converted to common impact measures such as excess mortality or habitat disruption. Impact assessment allows the interpretation of results from the LCI. The procedure for conducting LCA is standardized by the International Standards Organization (ISO) 14040 and 14044 series [13,14]. Broadly speaking, LCA approaches are of two types, Input-Output (IO) and process-based. While IO approach uses the country's economic inputs (material) and outputs (emission) based on industry sectors, the process-based approach is detailed and track individual processes used in the manufacture and transport of the product. On one hand, IO approaches are not specific to any one type of manufacturing process of a product rather a cumulative effect of all products of the sector under investigation (e.g., cement manufacturing will report data related to all energies used up and emissions emitted by the sector). In the U.S., the publicly available software tool, EIO-LCA [16] is widely used for IO approaches. On the other hand, process-based approaches are very specific to a process, i.e., detailed about all materials and energies used to calculate related environmental impact. For process-based approaches, there are several commercially available software to perform such assessments. Examples include GaBi [17], SimaPro [18], Athena Impact Estimator [19] etc. GaBi is an LCA software tool with a comprehensive database that is continuously updated from

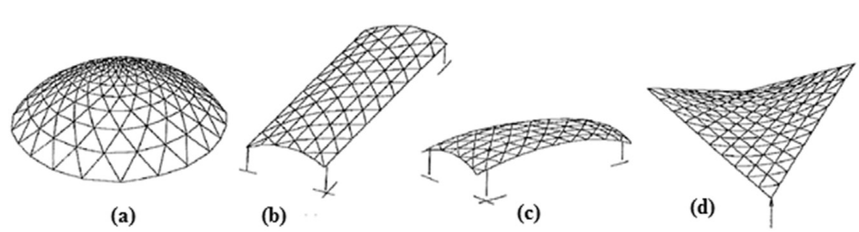

Fig. 2. Examples of reticulated space structures a) dome, b) barrel, c) toroid, d) hypar.