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Benefits of Integrating Advanced Composite Materials Into Modular Construction For Enhanced Structural Performance

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Abstract: Building projects in a variety of industries can now be completed more quickly and affordably with the use of modular construction. Nonetheless, there are still difficulties in keeping the benefits of modular construction while guaranteeing sustainability, durability, and structural integrity. To overcome these issues and open up fresh possibilities for modular building innovation, this study suggests looking at the integration of modern composite materials. High-performance concrete mixes, carbon fibre composites, and fiber-reinforced polymers (FRPs) are examples of advanced composite materials that offer special qualities such high strength-to-weight ratios, corrosion resistance, and design flexibility. Modular building has the potential to outperform traditional materials in terms of structural performance, longevity, and sustainability by using these attributes. In order to attain data saturation, this study performed seven virtual interview sessions to examine the integration. Those who participated in the interviews included project managers, modular building experts, senior managers from building-related firms, and officials from government construction agencies. A thematic approach was used to conduct a detailed analysis of the data gathered from these interviews. The findings of the study will further the comprehension of the benefits of using cutting-edge composite materials into modular buildings. The results will also influence industry standards, regulatory frameworks, and design guidelines in order to facilitate the broad use of composite-modular building systems.

Keywords: Modular construction, Advanced composite materials, Structural performance, Sustainability, Innovation, Life-cycle assessment

1 INTRODUCTION

The notion of sustainable development has grown near exponentially since the early 1990s; it is an important issue which aims to minimise the irreversible damage to the planet caused by human activity (Xu et al., 2020). This is achieved by considering the environmental, economic and social effects throughout the life cycle of a product. Development of more sustainable forms of industry, promote the use of recycled materials, produce longer lasting products, and decrease wastage. The construction industry which accumulates 40% of the total landfill waste has targets to develop sustainable techniques and to produce sustainable buildings. Thai et al., (2020) argued that the light steel framing industry for example, is sustainable and has vast potential to reduce the environmental impact. The study marks the transition of the steel industry from explaining how steel in construction can be judged to be sustainable to an approach where steel can lead in delivering sustainability in construction. This solidifies the previous statement but also opens an alternative approach of utilising advanced composite materials (ACM) in conventional and module construction. Specifically, advanced composite materials such as composite materials offer light weight options in replacement of heavy materials, recycled possibilities, and a life cycle longer than that of the intended building (Abdelmageed & Zayed, 2020; Otasowie et al., 2024). This suggests that the usage of advanced materials has potential to provide more sustainable buildings through the adoption of modular construction.

Modular construction is a process in which a building is constructed off-site, under controlled plant conditions, using the same materials and designing to the same codes and standards as conventionally built facilities, but in about half the time (Zhang et al., 2020). The building is in the form of modules, or 3-dimensional sections or volumetric units, that are then placed onto foundations and assembled to form the final structure. Modules can be placed side-by-side, end-to-end, or stacked, allowing for a variety of configurations and styles. This approach relates directly to the enhanced construction technologies research theme and is the primary construction method that would be used in conjunction with advanced materials or structural systems in a building project (Subramanya et al., 2020). The current process for constructing a building's modules is already heavily automated to take advantage of cost savings, speed of production, and quality improvements over traditional stick-built methods. Advances in this area has been concurrent with developments in construction robotics and automation aiding acceptability of modular construction (Adekunle et al., 2023). This existing approach and its potential future enhancements would constrain the new materials and systems to be backwardly compatible with conventional construction methods, while providing added benefits in the areas of environmental impact, construction efficiency, and worker health and safety. This will help to ensure cost effective utilization and smooth transition to integrated systems.

The integration of advanced composite material is a fundamentally new approach to the application of composites in construction, which differs from the typical use of composites as a substitute to traditional materials (Mousavizadeh et al., 2020). Common substitution has had limited success due to increased material and labour costs, with only a few niche applications in the construction market such as architectural features and bridge structures. This research will explore advanced composite materials in a modular system application which takes advantage of their high strength and fatigue resistance. The unique formability and ability of the materials is to be tailored for performance enhancements. It is the hypothesis of this research that a marriage of material efficiency in construction with high performance materials design will have a positive impact on consumer welfare and life-cycle assessment. This will be accomplished through the integration of an advanced composite material system into modular construction in an effort to enhance the overall structural performance and safety of material efficient systems. The objective of this paper is to introduce a novel modularity concept offering an advanced method to assemble new and retrofit existing buildings using prefabricated modular units incorporating advanced composite materials. The goal is to encourage a system that will significantly reduce building construction time, reduce the amount of skilled labour required, and produce a sustainable, economical structural system. This will be achieved by conducting a qualitative study on the benefits and perceived outcome of integrating of advanced composite materials and modular construction to create a unified, sustainable, structural, infrastructural system. The study will involve both analytical investigation and interview of construction materials experts.

2 METHODOLOGY

The study principally employs qualitative data to learn more about the participants' perspectives. This strategy is in line with the methodology used by Razkenari et al. (2020), who took a qualitative approach to learn how stakeholders in the building industry felt about modular construction. Table 1 shows seven structured virtual interviews were used to gather the data, and data saturation was effectively attained. This methodology is similar to that used by Aziz & Zainon (2022), who similarly collected data using a qualitative approach with five seasoned participants. The purpose of their study was to look at what motivates the construction sector to adopt lean BIM. Microsoft TEAMS was utilised to conduct the virtual interviews. A thematic analysis was then performed on the data gathered from these interviews. Neis & Neil (2023) also stressed the need of organised interviews in gaining a true knowledge of respondents' viewpoints. The main focus of the interview questions was to inquire about the advantages of using modern composite materials into modular construction to improve structural performance and stability. This is the research topic of the study. To assure the representativeness of the interviews, the study used purposive and snowball sampling strategies, following the methodology described by Teddlie and Tashakkori (2010). According to Naderifar et al. (2017), purposive sampling comprises the intentional selection of respondents, whereas snowball sampling involves the selection of available samples to contribute to the study. As shown in Table 1, the study sample included a variety of participant categories, such as senior quantity surveyors working on projects related to modular construction (E4-E5), project managers with experience in construction materials (E6-E7), and structural engineers conducting research on construction materials (E1-E3). The average length of each interview session was twenty minutes. A pilot study with two interviewees was carried out to improve the interview procedure and questions, and the researchers made some modifications in response. The data was analysed using the theme analysis method, as described by Ebekozien (2024). In order to reach data saturation, the research performed a total of 6 interviews between December 2023 and February 2024. After learning about the main goal of the study, the respondents indicated that they would be willing to participate without feeling compelled to. The study participants provided their comments anonymously, and ethical best practices were scrupulously followed. The study used open coding of meaning units from the obtained data during the data analysis phase. Five themes were created from the study using ATLAS.ti software, following the guidelines provided by Soratto et al. (2019). An independent practitioner was enlisted to cross-verify the developed themes in order to guarantee the validity of the analysis.

Table 1: Demography of Interviewees

ID	Profession	Years of Experience	Job Description
E1	Structural Engineer	15	Researcher/Academics
E2	Structural Engineer	12	Researcher/Academics
E3	Structural Engineer	18	Site Engineer
E4	Quantity Surveyor	13	Contractor
E5	Quantity Surveyor	12	Consultant
E6	Project Manager	10	Contractor
E7	Project Manager	7	Contractor

3 FINDINGS AND DISCUSSION

Research into the benefits of advanced composite materials for modular construction to attain structural performance and sustainability is vital. Discussed below are the themes of the benefits and outcomes.

Load-bearing Capacity (Theme 1): this subsection revealed that the integration of advanced composite materials will enhance load-bearing capacity of the modular buildings. All the participant agreed that advanced composite material plays a pivotal role to achieving more efficient transfer of loads in modular buildings. ACM possess exceptional strength-to-weight ratios and structural properties, making them well-suited for enhancing the load-bearing capacity of modular components and structures. The findings align with those of Sun et al. (2022) that incorporating composite materials into load-bearing elements such as beams, columns, and panels, modular construction can achieve greater structural stability and resilience, enabling the construction of taller buildings and larger spans without compromising safety or performance.

Wang et al. (2022) opined that the integration of ACM has clear economic implications as the improved load bearing capacity has the potential to greatly reduce the size and/or number of portal elements required for a composite structure to support a given magnitude of vertical load. Composite materials are now increasingly being used in load bearing structural applications. (Qin et al., 2022). The superior strength and stiffness that can be achieved relative to the density of these materials makes them an attractive alternative to conventional engineering materials such as steel, aluminium, and concrete. The specific character of composites means that anisotropic and non-linear material behaviour can be utilised to its full extent, but at the same time, this brings with it greater complexity in material and structural modelling if the full benefits of advanced composite materials are to be realised.

Structural Integrity (Theme 2): this subsection highlight structural integrity as one of the benefits of integrating ACM into modular construction. The ability to carry load is only one aspect of the structure. The true test of an advanced material in the sense of structural performance is its ability to maintain a high level of integrity (Dahal et al., 2022). Structural integrity is the ability of an item to hold together under a load, including its own weight, without deforming too much. It refers to the capacity of a structure to support loads without being deformed, excessively cracked, or broken. Basically, a material with high structural integrity is one which is strong, stiff, and tough (Promhuad et al., 2022; Malabadi et al., 2023). Stiffness is not to be confused with strength. A material may be very strong but not stiff. Likewise, it may be stiff but fail under a high load because it has low strength. Stiffness is a measure of how much force is required to deform a material. High stiffness typically means high load-bearing capacity. Toughness is a material's capacity to absorb energy before failure. Interviewee P1, P2, P5 & P6 noted that a tough material can have high strength, but if it cannot absorb much energy, it will fracture easily. This aligns with the study of Ahmed et al., (2022), revealing that the materials in both the hemp-based composite and fiber-reinforced plastic performed well in terms of structural integrity. The load-bearing capacity results based on P5 & P7 experience showed that both ACMs supported much higher loads than their predecessors, i.e., traditional construction materials, with the hemp composite reaching ultimate loads similar to modern construction steel beams. High strength and deformability ratio found in Hemp beams show that they can also have potential for high toughness as compared to conventional materials. The materials also only started to fail after reaching peak loads, meaning that they did not have a sudden loss of strength. This is an important factor in the safety of structures as sudden failure gives little or no warning. The brittle material failure of the fiber-reinforced plastic may be viewed as a negative result in terms of energy absorption, but the material still demonstrated high stiffness and load-bearing capacity as opined by Pokharel et al., (2022). This also indicates high stiffness and good load support and suggests that the material can be further optimized to increase strength and toughness.

Durability (Theme 3): P1-P7 revealed that ACMs have high durability and it can only be concluded that these materials will enhance the durability of modular systems. However, it is hard to directly compare the results to the baseline timber systems, and thus timber systems can only be said to have inferior durability. The glass fibre-reinforced polymers (GFRP) for example show valuable ductile post-peak behavior when testing metallic connections and show strain recovery from creep in bolted timber connections (Saad & Lengyel, 2022). This is a desirable form of behaviour as the connections will begin to lose bearing capacity and form holes around the connections over an extended period of service. Interviewee P1, P2, P3 agreed that the GFRP concrete connectors show very little damage after environmental testing, other than some micro cracking around the holes, and are far stiffer than the steel connectors. Composite materials generally consist of two or more chemically distinct phases. The load-bearing elements are almost always fibers (e.g. carbon or glass) within a matrix, though the matrix also has a structural function. Durability is the ability of a material or structure to fulfil its design function over an extended period of time, and is a function of the materials and the anticipated lifetime of the structure (Yeboah & Gkantou, 2021; Otasowie et al., 2024). Clearly, the highest possible durability is desirable for a building, particularly for load-bearing and primary structures and in the case of anticipated long service life. Durability is considered in many contemporary design codes, often implicitly, and specific requirements may be given for different parts of a building. High durability in advanced composites is achievable and results from both the fibers and the matrix as observed by Shekarchi et al., (2020). Inorganic fibers generally have good durability, but the organic fibers and matrices are susceptible to environmental degradation from moisture and ultraviolet radiation. This can be a problem in some applications, though organic matrix composites can be formulated with good durability. In any case, the composite has the advantage of allowing the designer to place the high durability material only where it is needed. This and the low maintenance requirements resulting from good durability make composites an economical choice in the long term.

Seismic Resistance (Theme 4): This subsection highlight material ductility as a factor that can enhance seismic resistance. High brittle materials will exhibit explosive-type failure upon reaching ultimate strength, where the entire structure can fail in a very short period of time. Material ductility will allow for gradual energy dissipation and increased load resistance after reaching ultimate strength. This will increase the safety of the structure during an earthquake and allow for repair after damage has occurred. A ductile wall can be designed using a dual skin with dissipative bracing frame (Hirsch et al., 2021; Gonzalez et al., 2017). A dissipative bracing frame is an energy-dissipating frame connected to the wall that can reduce damage to the building. P3 stated that "during a seismic event, the dissipative frame will sway, dissipating energy and protecting the wall. If damage does occur, the frame can be easily replaced." Integration of advanced composites can address these problems through improved joint design and increased material durability (Wahab et al., 2023; Otasowie et al., 2024). As discussed previously, bolting angles inside the wall of a module can be made more earthquake resistant through the use of FRP. This will increase the lateral resistance of the wall, improving overall structural integrity. Damage to the bolt angles may cause failure in the joint. If bolt angles are anchored to adjacent walls from the front and back sides, this mode of failure can be avoided. The bolt angles can be anchored using through-bolts. This is simply done by drilling holes through the bolt angles and the adjoining wall and fastening the holes with a bolt. Failure can be further prevented with back-up angle supports. If damage occurs, the support will transfer the load to prevent folding at the angle. With the use of joint reinforcement, failure at the wall-to-wall joint during a seismic event can be prevented. Seismic resistance of a structure defines how well the structure will be able to withstand and protect its integrity during a seismic event (Ou et al., 2019). The nature of modular construction is that the building is assembled on-site from factory-built modules. This means the structure is less permanent during construction and certain parts of the building may be weaker due to damage from transportation. Should an earthquake occur during construction, a module building may be more susceptible to damage as the modules are designed to be assembled and disassembled repeatedly. The ability to withstand multiple assemblies and disassemblies can reduce the life of the module, weakening the structure and causing folding at the joints.

Fire Resistance (Theme 5): When the modular structure under fire conditions is designed as a non-load-bearing construction, the fire safety requirements can be less rigorous (Kariyawasam et al., 2023). This design situation is typical of single-storey modular structures and multi-storey structures up to three storeys high. The floor and the modules may be designed as a membrane structure founded on the slab or may be supported on a framework with the modules acting as non-load-bearing infill. In both of these design formats, the floor and the modules are not required to have fire resistance. Use when the modular structure is required to have the same fire resistance as an equivalent permanent structure, it may be necessary to conduct tests to determine the contribution that the individual materials used in the structure make to the fire. In practice, it is unusual for a manufacturer to use materials that have a lower resistance than required because the same materials are often used in permanent construction. This aligns with the studies of Otmani Benmehidi et al., (2014) & Kariyawasam et al. (2024) that the modular structure will benefit from enhanced fire safety in comparison to an equivalent temporary cabin construction. This is due to the overall higher requirement for permanent buildings and the need to comply with the regulatory reform for buildings used as workplaces as this legislation is enforceable against the occupier. It is expected that the modules will also exhibit a good level of fire resistance for their weight. This is important in constructions such as schools and hospitals where fire compartmentation is essential and the modules will be supporting a platform or frame structure.

4 CONCLUSION AND RECOMMENDATION

In conclusion, the concept of implementing ACM into the modular housing industry will revolutionize the way homes are constructed and also the significance of ACM to the structural engineering community. It is apparent from this study that doing so would increase disaster resilience in infrastructure. Despite the shortage of studies on the topic, ACM panel's resistance to extreme loading conditions and beneficial ductile behaviour presents significant advantages over traditional materials, especially in seismic regions. Moreover, the increased strength to weight ratio would assist in relocating buildings to hard-to-reach locations due to the ease of transportation and foundation costs. The lay-up process of ACM panels allows for a degree of customization that would see improvement from future development of modular construction methods and presents a way for engineers to easily create and test complicated structural forms. This is an exciting prospect, as increasing the architectural capabilities of modular construction may also increase public perception. With this, the ability to provide affordable housing that does not compromise architectural quality would make modular construction a viable option for housing provision across all sectors of society. Using ACM panels would also increase sustainability and reduce the cost of modular buildings lifetime, both at the consumer and manufacturer level. This study has proven that the long-term durability and low maintenance requirements of infrastructure built from ACM surpass that of conventional construction materials. At only a slight increase in initial building costs, this has the potential to shift the lifecycle cost analysis of modular homes, and with the reducing environmental footprint of ACM production, this concept would be an attractive prospect for the future. Finally, it should be noted that this study has been done to contribute to a sustainable society in the future. Restrictions on climate change and effective utilization of energy are becoming ever greater issues, and to solve these issues, steps must be taken from this generation to conserve resources and find renewable energy. Housing and its construction are greatly related to this cause, and it is important that the housing industry shift away from conventional building methods to more sustainable methods. However, considering the ever increasing population of the world, housing demand will further increase and thus it is necessary to balance the demand and environmental issues. In current situation, housing in developed countries will not consume less resources and energy as long as people keep returning to purchase new homes and it is evident that the industry must find a way to make existing homes durable and reusable. At this juncture, modular housing is the key to the future, and the result of the research can provide a great contribution to our target of making durable and reusable homes by enhancing the structural performance of modular construction.

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