INTRODUCTION

It is more important today than ever before that we find solutions for our rapidly urbanising world in order to provide housing for the billions of people who will live in our cities in the coming decades. Dense urban environments characterised by tall buildings can accommodate population growth while also being environmentally sustainable, but only if the development takes place responsibly.

This project describes a new structural system made from BFRC that represents the first significant challenge to concrete, steel and wood structures. The proposed system is made from a material with very unique properties and has the potential to revolutionise the building industry. The particular characteristics that BFRC possess arise from the properties of its individual components, bamboo and polymer. Bamboo is one of the most significant, diverse, and robust building materials ever provided...
to man by nature and is readily available, renewable, durable and strong.

Polymers are a material consisting of any of a wide range of synthetics that are malleable and therefore can be molded into objects of almost any shape or size. Polymers are an ideal material to be used in the construction industry due to the many benefits the material offers including its resistance to fire and rot, lightweight, low cost, and color variety. Melding bamboo within a polymer matrix makes BFRC an exemplary building material that possesses both high tensile strength and compressive strength as well as resistance to fire, insects, rot and ultraviolet light.

This study is the beginning of a path to realising built projects using a material that harnesses and utilises unique characteristics from both a man-made substance as well as nature-made fibre. The demand for tall buildings will continue to grow along with the ever-increasing global population; however, to build sustainably and to begin reducing carbon dioxide emissions, a new material is needed for the construction of tall buildings.

THE NEED FOR TALL BUILDINGS

Reduce Travel Times

In general, tall buildings are recognised as an efficient type of compact development within an urban setting that helps reduce travelling distances and carbon emissions. Compact developments are needed due to the outward expansion of cities into the suburbs resulting in ever-increasing travel times, energy consumption, and CO₂ emission [1]. Tall buildings can accommodate many more people with a much smaller building footprint than with low-rise building on the same amount of land. Fig. 1 shows the result of an excessive number of people depending on vehicular transportation to move from one place to another.

![Fig. 1](image1.jpg) Heavy congestion during rush hour in Shanghai. (China “Traffic Congestion, Part 2: To Build Or Not To Build… - Architectural Centre - Wellington, New Zealand, Architecture, Design”. Architecture.org.nz N.p., 2016. Web. 26 Nov. 2015).

Prevent Urban Sprawl

Urban sprawl, a pattern of uncontrolled development around the periphery of a city, is an increasingly common feature of the built environment in the United States and other industrialised nations (Fig. 2) [2]. Not only is urban sprawl problematic with regards to the environment, there is also evidence pertaining to a variety of health problems associated with it as well. Some of these health problems include obesity, diabetes, cardiovascular disease and respiratory disease [3].

Improve Environmental Quality

By maximising building area with a minimum physical footprint, tall buildings can help provide for dense arrangements and help in the preservation of open spaces by allowing many more people onto a smaller amount of land (Fig. 3). The availability of open spaces provides crucial environmental and health benefits that include improvement of air pollution, regulation of temperature, reduction of noise, handling of wind currents, flood prevention, and surface and ground water resources safeguarding from contaminants such as chemicals and trash.

Population Growth

Today, nearly 50% of the total world population (about 7.3 billion people), live in an urban setting. This transition will occur at an increasing rate over the next few decades as the suburban populations migrate and become city dwellers. By 2030, it is expected that about 60% of the world’s population will be urban. As the trend continues, by 2050, over 80% of the world population will live in urban areas when the world’s population is expected to reach 9.7 billion (Fig. 4) [4].

![Fig. 2](image2.jpg) Urban sprawl as a result of uncontrolled development around the periphery of cities. (Editorial Commercial Stock | Fritz Mueller Photography - Urban Sprawl In Northwest Calgary, Alberta”. Editorial Commercial Stock | Fritz Mueller Photography. N.p., 2016. Web. 26 Dec. 2015).
THE NEED FOR ALTERNATIVE BUILDING MATERIALS

Nearly all tall buildings today use some combination of concrete and steel for the primary structural elements for two reasons. First, non-combustible materials are required for most buildings greater than four stories tall. Second, concrete and steel have higher material strengths than wood. These factors have generally limited wood use to low-rise buildings.

Recently, developments in mass timber technology are overcoming these challenges. Cross-laminated timber is made of small dimensional lumber components and structural adhesives and can be used for various structural elements with sizes available up to 40 feet in length. However, the sustainability of wood seems to be an equally important consideration in the resurgence of multi-storey timber buildings.

Concrete

Concrete has a large carbon footprint and is a highly energy intensive material to produce. As the world’s understanding of climate change evolves, it is becoming more evident of the impact that buildings contribute to the greenhouse gases causing climate change. Concrete production alone represents roughly 5% of world CO₂ emissions [5]. Cement is manufactured from a combination of naturally occurring minerals (calcium, silicon, aluminum, iron and small amounts of other ingredients) and heated in a large kiln to over 2700°F to convert the raw materials into clinker; Fig. 5 illustrates this process. The amount of carbon dioxide produced from the calcination process is approximately 0.55 kg CO₂ per kg cement clinker. As a comparison, the production and transportation of concrete represents more than 5 times the carbon footprint of the entire airline industry [6].
Steel

The steel industry is a major consumer of electricity, used to power its lengthy production process (Fig. 6); virtually all of the greenhouse gas emissions relate to energy consumption. Although there are no direct emissions of CO$_2$ associated with the manufacturing process, large amounts of electricity are required (primarily with coal and gas fired energy sources) for each step the production process. Energy consumption for the production of steel represents roughly 3% of domestic energy use and 8% of all U.S. manufacturing energy use [7].

Wood

Wood is typically the ideal material available for building structures with respect to embodied energy and carbon emissions. The manufacturing process of wood products also requires less fossil fuel-based energy and is responsible for far less carbon emissions than those of concrete or steel. While this is true, wood construction has its own set of negative environmental attributes that cannot go unnoticed. As previously mentioned, trees act as carbon sinks by absorbing CO$_2$ from the atmosphere and releasing oxygen for animals to breathe. As humans continue to exhaust more carbon dioxide in the air, the need for trees to remove that carbon dioxide from the air increases. Since building with wood requires the cutting down of trees, this contributes to the global problem of deforestation [8].

Tall Wood Buildings

Tall wood buildings are not a new concept but were constructed centuries ago. Over 1400 years ago tall wood pagodas up to 19 stories tall were built in Japan and still stand today. As technologies evolve, modern ingenuity has triggered a race for to create many more tall wood buildings worldwide. In the last 5 years, 17 tall wood buildings have been built around the world that are over 7 storey in height, including the 9-storey Stadthaus residential building in London, the 7-storey Tamedia office building located in Zurich, Switzerland, and Forté, the tallest to date, a 10-storey residential building in Melbourne, Australia.

Deforestation

Within earth’s history, massive extinctions have occurred five times, the last occurring 65 million years ago with the extinction of the dinosaurs. Scientists are calling what is occurring now, the sixth mass extinction. Rainforests cover less than 2% of the earth’s total surface area, yet they accommodate nearly 50% of all the earth’s plants and animals. Deforestation causes the loss of over 137 animal and insect species per day, totaling to more than 50,000 species per year [9].

The United Nations estimates that over 100,000 acres of rainforests are destroyed each day. The world has already lost 50% or 75 million acres of its temperate rainforest, mostly in just the last 40 years [10].

Global Warming

Global warming, sometimes referred to as climate change, is the increase in the average temperature of the Earth’s atmosphere and oceans as a result of the buildup of greenhouse gases in our atmosphere. Global warming is a serious threat that scientists believe is the cause of sea level rise, extreme weather, changes in agricultural yields, glacier retreat, species extinctions and increases in disease [11]. These issues are significant for living conditions since they will profoundly impact urban environments on a global scale. Fig. 7 shows atmospheric concentrations of carbon dioxide over the past 400,000 years as expressed in units of parts per million by volume (ppm) [12].

METHODODOLOGY

What are Bamboo Fibre-reinforced Composites?

The anatomical properties of bamboo fibre make bamboo a superior renewable source when compared to all other known natural ligno-cellulosic fibres. Fibres from the bamboo plant are separated and sized in the form of individual fibres or strips. These fibres or strips are then informally imbedded within a polymer matrix (epoxy, unsaturated polyester resins or similar). Processes have been developed through trials and research in order to cast bamboo fibre reinforced composites (BFRC) unidirectionally, bi-directionally and multi-directionally via compression molding, extrusion or pultrusion methods. The resulting material combines the strength and resilience of bamboo fibre with dimensional stability and moisture resistance of polymer resins. Due to its
incredibly rapid growth cycle and the variety of areas in which it is able to grow, bamboo is also an inexpensive resource. With such rapid growth, bamboo plants absorb large quantities of CO$_2$, three to four times more than most trees, meaning that its cultivation as a building material would help reduce the rate of climate change [13].

**Material Research**

Synthetic fibres have been used as reinforcement for many years within the composites industry; however natural fibres offer many benefits and are therefore gaining much momentum as a synthetic fibre substitute in various applications. The combination of natural fibres with polymer matrices can produce products that are competitive with synthetic composites in terms of weight, strength and cost [14].

For the purpose of this research project, numerous articles were referenced relating to the study and physical testing of bamboo fibre-reinforced composites. Fig. 8 shows a comparison of bamboo with other construction materials.

**Timber Tower Case Study**

This case study was done on the Dewitt Chestnut building, which was constructed in Chicago, Illinois in 1966. The 42-storey residential tower was designed by Skidmore, Owings and Merrill (SOM), uses a reinforced concrete flat plate floor system with framed tube columns and stands nearly 400 feet tall [15].

**Design Approach of the Timber Tower**

SOM’s design approach is to replace specific structural elements of the original concrete framed tube structural system with mass timber components (see Fig. 9). The objective for the project was to develop a structural system for tall buildings that uses mass timber for the structural elements in order to minimise the embodied energy of the building. While the proposed mass timber structural system is feasible, additional research and testing is necessary to confirm material performance and safety [15].

**Structural System**

The system was developed around two major design criteria for tall buildings. The first is to deal with the lateral loads, which is done with a reinforced concrete tie-beam that runs around the perimeter of each floor creating a web through the core of the structure. This system is designed to deal with both wind and seismic forces and is linked with the mass timber shear walls located at the core of the structure. These shear walls are required to be 12” thick with mass timber (10” thick using BFRC) in order to handle both lateral and gravitational forces.

The second design criterion is to manage the gravity loads. In this case, 18 mass timber columns measuring 24” × 24” run the parameter of each floor. When the composite is used to replace the mass timber, the column sized can be reduced to 18” × 18”. The floor-to-floor height for this timber tower is 9’-0” with 8” thick mass timber floor slabs. The composite allows the floor slab thickness to be reduced to 6’ resulting in a floor-to-floor height reduction of 2” and the overall building height to be reduced by roughly 7’.

It should also be mentioned that the foundation, basement and first floor plaza use exclusively reinforced concrete. This is due to the unique nature of the material, which offers superior performance for these areas of construction. The mass timber is used from the second floor on up, 41 floors in total [15].

**Member Size Calculations**

Shown are the calculations made to determine the member sizes for the composite elements followed by

<table>
<thead>
<tr>
<th>Material</th>
<th>Bamboo Composite</th>
<th>Concrete</th>
<th>Steel</th>
<th>Wood</th>
<th>CLT</th>
<th>Glulam</th>
<th>ICL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile (ksi)</td>
<td>37.5</td>
<td>26.9</td>
<td>0.5</td>
<td>152.5</td>
<td>15.2</td>
<td>4.0</td>
<td>3</td>
</tr>
<tr>
<td>Compression (ksi)</td>
<td>13.4</td>
<td>11.1</td>
<td>4.4</td>
<td>116</td>
<td>1</td>
<td>4.1</td>
<td>3.6</td>
</tr>
<tr>
<td>Flexural (ksi)</td>
<td>21.5</td>
<td>0.3</td>
<td>0.6</td>
<td>58</td>
<td>10.8</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>Elastic Modulus (ksi)</td>
<td>2,200</td>
<td>1,705</td>
<td>4,000</td>
<td>28,000</td>
<td>3,900</td>
<td>5,600</td>
<td>3,900</td>
</tr>
<tr>
<td>Shear (ksi)</td>
<td>3.6</td>
<td>0.3</td>
<td>1.7</td>
<td>10.8</td>
<td>1.5</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Density (lb/ft$^3$)</td>
<td>57.5</td>
<td>22</td>
<td>135</td>
<td>300</td>
<td>42</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>Embedded Energy (kWh/g)</td>
<td>12</td>
<td>0.016</td>
<td>1.6</td>
<td>24</td>
<td>2.5</td>
<td>1.2</td>
<td>1.2</td>
</tr>
</tbody>
</table>

**Fig. 8** Material comparison of bamboo fibre-reinforced composites with other construction materials.

**Fig. 9** Section cut showing the new design approach using mass timber to replace specific reinforced concrete elements. (Timber Tower Research Project. 1st ed. Chicago: Skidmore, Owings, and Merrill, 2013. Web. 11 Dec. 2015).
calculations that were made to estimate total carbon emission, building weight as well as volume of material required based on the material used.

Columns

Basic Data:
- \( F_b \), flexural stress = 20,000 psi
- \( F_c \), compressive stress = 13,000 psi
- \( F_t \), tension parallel to grain = 40,000 psi
- \( E \), modulus of elasticity = 2,500,000 psi
- \( C_m = 1.0 \)
- \( C_t = 1.0 \)
- \( C_i = 1.0 \)
- \( A = 18 \text{in} \times 18 \text{in} = 324 \text{in}^2 \)
- \( I = 90 \text{in}^4 \)
- \( d_L = 18 \text{in} \)

\[ F'_{cm} = F_{cm}(C_D)(C_M)(C_T)(C_F)(C_P)(C_i) \]

where,
- \( C_M \) = Wet Service Adjustment Factor
- \( C_T \) = Temperature Factor
- \( C_F \) = Size Factor
- \( C_i \) = Incising Factor
- \( C_P \) = Column stability factor = NDS Eq. 3.7-1
- \( C_D \) = Time Adjustment Factor

\[ C_r = \beta - \sqrt{\frac{\beta^2 - \alpha}{\alpha}} \]

\[ \beta = \frac{1 + \alpha}{2c} \]

\[ \alpha = \frac{F_{cm}}{F'_{cm}} \]

\( F_{cm} \) = nominal Euler critical buckling stress for columns

\( F'_{cm} \) = compressive design value in column at zero slenderness ratio

\( F_{cm} \) = compressive design value parallel to grain multiplied by all adjustment factors except

\[ F_{cm}(C_M)(C_T)(C_F)(C_P)(C_i) \]

\[ F_{cm}(C_M)(C_T)(C_F)(C_P)(C_i) \]

\( E'_{min, n} \) = adjusted modulus of elasticity for column buckling

\( E'_{min, n} = \frac{0.022F'_{min,n}}{E'_{cm}} \)

\( C'_{r} = \text{buckling stiffness factor for 2 × 4 and smaller compression chords in trusses with 3/8 in or thicker plywood nailed to narrow face of member} \)

\( C_P = \text{size factor for compression. Obtain values for visually graded dimensional lumber from the adjustment factors section of NDS supplement tables} \)

\( 4A \) and \( 4B \)

\( = 1.0 \) for sawn lumber in B&S and P&T sizes and MSR and MEL lumber

\( = 1.0 \) for glulam

\( l_e = \text{Effective length} = \text{distance between inflection points} \)

\( = \text{effective length factor} \times \text{unbraced length} \)

\[ l_e = K_e \times l \]

\( = 10ft × 12 = 120 \text{in} \)

\[ E' = E(C_M)(C_T)(C_F)(C_P) = 250,000 \times 1.0 \times 1.0 \times 1.0 = 2,500,000 \text{psi} \]

Modulus of elasticity for column buckling:

\[ F_{cb} = \frac{0.822F_{cm}^2}{(l_e/d)^2} = \frac{0.822 \times 2.5 \times 10^6}{(120/8)^2} = \frac{2,055,000}{6.667} = 308,250 \text{psi} \]

Compressive stress for column buckling:

\[ F_c = F_{cb}(C_D)(C_M)(C_T)(C_F)(C_P)(C_i) = 13,000 \text{psi} \times 1.6 × 1 = 20,800 \text{psi} \]

Stability Adjustment Factor:

\[ \alpha = \frac{F_{cb}}{F_{cm}} = \frac{308250}{20800} = 14.82 \]

\[ \beta = \frac{1 + \alpha}{2c} = \frac{(1+14.82)(2)(0.9)}{8.788} = 8.788 \]

\[ C_r = \beta - \sqrt{\frac{\beta^2 - \alpha}{\alpha}} \]

NDS Eq. 3.7-1 \( C_p = 8.788 - \sqrt{[8.788]^2 - \left(\frac{14.82}{0.9}\right)} = 0.9 \)

Allowable compressive strength:

\[ P_{allow} = A \times F_c = 324 \text{in}^2 \times 18,720 \text{psi} = 6,065,280 \text{lbs} \]

Therefore, the column is adequate.

Beams

Flexural strength is given by:

\[ F_{b,x} = F_{b,x}^*(C_D)(C_M)(C_T)(C_i) \]

or

\[ F_{b,x} = F_{b,x}^*(C_D)(C_M)(C_T)(C_F)(C_P)(C_i) \]

where,

- \( C_M \) = Wet Service Adjustment Factor
- \( C_T \) = Temperature Factor
- \( C_F \) = Size Factor
- \( C_i \) = Beam Stability Factor
- \( C_v \) = Volume Adjustment Factor
Beam stability factor:

$$C_L = \beta = \beta - \frac{1}{\alpha} = 1.26 - \frac{1.26^2 - 1.4}{1.9} = 0.34$$

However, if this beam is going to be fully laterally supported then,

$$C_L = 1.0$$

Thus, the flexural strength would be:

$$F'_{bxm} = F'_{bem}C_DC_MC_L = 20,000 \times 1.6 \times 1.0 \times 1.0 \times 0.34 = 10,880 \text{ psi}$$

Section Modulus:

$$S_{xx} = \frac{\text{Width} \times \text{Depth}^2}{12} = \frac{12(16in)}{12} = 512 \text{ in}^3$$

Bending moment capacity

$$F'_{b} = \frac{5 \text{ k/ft}}{28.5^2} = 464 \text{ k-ft}$$

Estimated bending moment on the beam

$$= (5 \text{ k/ft})(28.5^2)/12 = 338 \text{ k-ft}$$

Therefore, the beam section is adequate.

Floor Slabs

Bamboo fibre-reinforced composites for tall buildings

Flexural strength is given by:

$$F'_{b} = F'_{bem}(C_D)(C_M)(C_t)(C_f)F'_{bem}$$

$$= F'_{bem}(C_D)(C_M)(C_t)(C_f)$$

$$F'_{bem} = F'_{bem}(C_D)(C_M)(C_t)(C_f)$$

Beam stability factor:

$$C_L = \beta = \beta - \frac{1}{\alpha} = 1.26 - \frac{1.26^2 - 1.4}{1.9} = 0.34$$

However, if this beam is going to be fully laterally supported then,

$$C_L = 1.0$$

Thus, the flexural strength would be:

$$F'_{bxm} = F'_{bem}C_DC_MC_L = 20,000 \times 1.6 \times 1.0 \times 1.0 \times 0.34 = 10,880 \text{ psi}$$

Section Modulus:

$$S_{xx} = \frac{\text{Width} \times \text{Depth}^2}{12} = \frac{12(16in)}{12} = 512 \text{ in}^3$$

Bending moment capacity

$$F'_{b} = \frac{5 \text{ k/ft}}{28.5^2} = 464 \text{ k-ft}$$

Estimated bending moment on the beam

$$= (5 \text{ k/ft})(28.5^2)/12 = 338 \text{ k-ft}$$

Therefore, the beam section is adequate.
Carbon Emissions

The following calculations were made to estimate carbon emissions, volume of material and building weight based on the material used to construct the building:

Original:
35,900 tons \times \frac{2000 \text{ lbs}}{\text{ton}} \times \frac{0.453592 \text{ kg}}{\text{lb}} = 32,567,900 \text{ kg}

Carbon Emissions (Tons CO}_2 \times 10^3\right)
Volume of Material (Cubic Feet × 10^3)

Tons \times 10^3
32,567,900 \text{ kg} \times 1.6 \frac{\text{ MJ}}{\text{ kg}} = 52,108,650 \text{ MJ}
52,108,650 \text{ MJ} \times \frac{0.11277 \text{ kg CO}_2}{\text{ MJ}} = 5,872,600 \text{ kg CO}_2
5,872,600 \text{ kg CO}_2 \times \frac{1 \text{ ton}}{6,600 \text{ kg}} = 12,947,000 \text{ lbs CO}_2
12,947,000 \text{ lbs CO}_2 \times 1 \frac{\text{ ton}}{2000 \text{ lbs}} = 6,473 \text{ tons CO}_2

Total: 6,473 tons + 35,900 tons (1 ton CO}_2 /1 ton concrete) = 42,373 tons CO}_2

Concrete:
10,600 tons \times \frac{2000 \text{ lbs}}{\text{ton}} \times \frac{0.453592 \text{ kg}}{\text{lb}} = 9,253,277 \text{ kg}
9,253,277 \text{ kg} \times 1.6 \frac{\text{ MJ}}{\text{ kg}} = 14,805,243 \text{ MJ}
14,805,243 \text{ MJ} \times \frac{0.11277 \text{ kg CO}_2}{\text{ MJ}} = 1,668,550 \text{ kg CO}_2
1,668,550 \text{ kg CO}_2 \times \frac{1 \text{ ton}}{6,600 \text{ kg}} = 3,468,478 \text{ lbs CO}_2
3,678,487 \text{ lbs CO}_2 \times 1 \frac{\text{ ton}}{2000 \text{ lbs}} = 1,840 \text{ tons CO}_2

Total: 1,840 tons + 10,600 tons (1 ton CO}_2 /1 ton concrete) = 12,040 tons CO}_2

Timber:
6,800 tons \times \frac{2000 \text{ lbs}}{\text{ton}} \times \frac{0.453592 \text{ kg}}{\text{lb}} = 13,600,000 \text{ kg}
13,600,000 \text{ kg} \times 1.6 \frac{\text{ MJ}}{\text{ kg}} = 21,768,851 \text{ kg}
6,168,851 \text{ kg} \times 12 \frac{\text{ MJ}}{\text{ kg}} = 74,026,214 \text{ MJ}
74,026,214 \text{ MJ} \times \frac{0.11277 \text{ kg CO}_2}{\text{ MJ}} = 8,342,754 \text{ kg CO}_2
8,342,754 \text{ kg CO}_2 \times \frac{1 \text{ ton}}{6,600 \text{ kg}} = 1,839,200 \text{ lbs CO}_2
18,392,600 \text{ lbs CO}_2 \times 1 \frac{\text{ ton}}{2000 \text{ lbs}} = 9,196 \text{ tons CO}_2

Total: 9,196 tons CO}_2

Sequestered CO}_2:
1 \text{ m}^3 \text{ wood absorbs} 1 \text{ ton CO}_2
341,600 \text{ ft}^3 \times 1 \text{ m}^3 / 35.3147 \text{ ft}^3 = 9,673 \text{ tons CO}_2

Total: 9,673 tons sequestered CO}_2

Composite:
7,768 tons \times \frac{2000 \text{ lbs}}{\text{ton}} \times \frac{0.453592 \text{ kg}}{\text{lb}} = 15,536,000 \text{ lbs}
15,536,000 \text{ lbs} \times 1 \frac{\text{ MJ}}{7,047 \text{ kg}} = 84,564,063 \text{ MJ}
84,564,063 \text{ MJ} \times \frac{0.11277 \text{ kg CO}_2}{\text{ MJ}} = 9,530,370 \text{ kg CO}_2
9,530,370 \text{ kg CO}_2 \times \frac{1 \text{ ton}}{2000 \text{ lbs}} = 21,010,844 \text{ lbs CO}_2
21,010,844 lbs CO₂ × \( \frac{1\text{ton}}{2000\text{lbs}} \) = 10,505 tons

Total: 10,505 tons CO₂ emission

Sequestered Carbon dioxide: 1m³ bamboo absorbs 3–4 tons CO₂

270, 200 ft³ × 1 m³ / 35.3147 ft³ = 7,651 tons

7,651 tons × 3.5 (average) = 26,780 tons

Total: 26,780 tons sequestered CO₂

### Building Weight Estimates

<table>
<thead>
<tr>
<th>Material</th>
<th>Original</th>
<th>Concrete</th>
<th>Timber</th>
<th>Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>482,000 ft³  ( \times \frac{1400}{27} ) (density)</td>
<td>67,480,000 lbs ( \times \frac{1\text{ton}}{2000\text{lbs}} ) = 33,740 tons</td>
<td>( \times \frac{1400}{27} ) (density)</td>
<td>20,496,000 lbs ( \times \frac{1\text{ton}}{2000\text{lbs}} ) = 10,248 tons</td>
<td>( \times \frac{1400}{27} ) (density)</td>
</tr>
<tr>
<td>146,400 ft³  ( \times \frac{510}{27} ) (density)</td>
<td>13,664,000 lbs ( \times \frac{1\text{ton}}{2000\text{lbs}} ) = 6,832 tons</td>
<td>( \times \frac{510}{27} ) (density)</td>
<td>( \times \frac{510}{27} ) (density)</td>
<td></td>
</tr>
</tbody>
</table>

### Composite Shear Walls:

| Large: 90” (height) × 324” (length) × 12” (thickness) | 349,920 in³ | 275,400 in³ × 4 = 1,199,680 in³ |
| Small: 90” (height) × 122” (length) × 12” (thickness) | 131,760 in³ | 131,760 in³ × 4 = 527,040 in³ |

### Exterior Walls:

| 90”(height)×255”(length)×12”(thickness) | 275,400 in³ | 275,400 in³ × 4 = 1,101,600 in³ |

### Composite Shear Walls:

| Large: 88” (height) × 324” (length) × 10” (thickness) | 285,120 in³ | 285,120 in³ × 4 = 1,140,480 in³ |
| Short: 88” (height) × 122” (length) × 10” (thickness) | 107,336 in³ | 107,336 in³ × 4 = 429,440 in³ |
| Exterior: 88” (height) × 255” (length) × 10” (thickness) | 224,400 in³ | 224,400 in³ × 4 = 897,600 in³ |

### Timber Floor Slabs:

| Largest: 309” (length) × 103” (width) × 8” (thickness) | 254,616 in³ | 254,616 in³ × 18 slabs = 4,583,088 in³ |
| Small: 288” (length) × 99” (width) × 8” (thickness) | 228,096 in³ | 228,096 in³ × 14 slabs = 3,193,344 in³ |

### Composite Slabs:

| Large: 309” (length) × 103” (width) × 6” (thickness) | 190,962 in³ |
| Small: 309” (length) × 103” (width) × 6” (thickness) | 171,072 in³ |

Total:

| Timber: 933,120 in³ + 1,399,680 in³ + 527,040 in³ + 1,101,600 in³ + 4,583,088 in³ + 3,193,344 in³ = 11,737,872 in³ = 6,792 ft³ × 41 floors = 278,472 ft³ |
| Note: 341,600 ft³(SOM estimate) - 278,472 ft³ = 61,130 ft³ unaccounted for |

Composite: 513,316 in³ + 1,140,480 in³ + 429,440 in³ + 897,600 in³ + 3,437,316 in³ + 2,395,008 in³ = 8,813,060 in³ = 5,100 ft³ × 41 floors = 209,100 ft³

Savings: 278,472 ft³ - 209,100 ft³ = 69,372 ft³

### Construction Sequencing

The proposed structural system is designed to be built in much the same way as that of a structural steel building. Mass timber is used for the primary structural elements such as the floors, columns, and shear walls and are connected using structural steel end fittings allowing for the erection of the timber elements to proceed up the building without immediate concreting of the joints. When timber is used, it will account for approximately 70% of the proposed structure, while only 30% will be reinforced concrete [15]. When BFRC are used, the only concrete needed is that of the foundation.

### Column Spacing

The location of columns along the perimeter of the building is set at approximately 24 feet on centre, which dictate the demising wall layout for the interior design. This column spacing requires the spandrel beams to quite large in order to handle both gravity and lateral loads; therefore a concrete spandrel beam was chosen due to the limited strength of timber beams [15]. However, based on the strength data collected, BFRC show to be of sufficient strength to replace the concrete spandrel beam component resulting in a further reduction of building weight as well as CO₂ emission.

### Floor-to-Floor Height

The floor-to-floor height of the original Dewitt-Chestnut building is 8'-9". The floor slabs are 8" which allow for an approximate floor to ceiling height of 8'-1" for the living area. The goal for the timber project was to match these heights but for this to happen the floor-to-floor height needed to be increased by 3". This was
This research investigated a previous case study that was done by SOM, and it was concluded that BFRC could not only be used to replace the mass timber elements that were proposed by SOM but could do so with improved results. By utilising the natural strength of the bamboo, the BFRC elements require smaller dimensions and therefore a lesser volume of material is needed for the structure. This results in an increase in leasable space, shorter floor-to-floor heights, and an overall lighter building. The reduced building weight leads to a smaller foundation size, which saves both time and money but also reduces carbon emissions. It was also concluded that by using BFRC for the structural elements of the building, the carbon emissions would be reduced far beyond that of a timber structure and ultimately results in a structure that sequesters more carbon than is emitted in the construction of the building. This cannot be said about any other construction material that exists currently.

The amalgamation of polymer matrix and bamboo fibres creates composites possessing ideal properties of each component. This unique combination results in a high quality sustainable building material made from a plant that is fast growing and is available in most parts of the world. The extensive research from every field such as architecture, construction technology, biological engineering, genetic engineering and cultivation are attempting to utilise bamboo fibre composites in the most effective way for the construction industry. The current era is the time for using bamboo fiber-reinforced composites for tall building construction.

**Reduced Carbon Emission**

The carbon emissions associated with the construction of the building are referred to as “embodied energy.” The carbon emissions of a building are associated with both the construction as well as the total energy consumed during its lifespan [16]. The total carbon footprint of the building is the sum of the operational carbon emissions plus the total carbon emissions produced during the construction of the building; the structure being the largest contributor due to the production of materials used in the structure. A comparison of CO₂ emission based on the materials used for the structure is shown in Fig. 10.

**CONCLUSION**

The attempt for this research study was to obtain information for the basic properties of BFRC and use the available strength values to predict the material performance when used in structural applications for tall building construction. Scientists and engineers worldwide have conducted a wide range of studies and continue to research BFRC to gain a better understanding of chemical modification, mechano-physical, thermal and other properties.

While much research continues to be done, there are still barriers obstructing the realization of a structural system comprised of bamboo composites. Before this building revolution can begin many things will need to happen including additional testing in material strength and longevity, as well as fire resistance engineering. However, results of this research suggest that construction of tall buildings using BFRC is not only technically feasible but may be superior to all other construction materials available today.

**REFERENCES**


Statement of originality of work: The manuscript has been read and approved by all the authors, the requirements for authorship have been met, and that each author believes that the manuscript represents honest and original work.

Sources of funding: None.

Competing interest / Conflict of interest: The author(s) have no competing interests for financial support, publication of this research, patents, and royalties through this collaborative research. All authors were equally involved in discussed research work. There is no financial conflict with the subject matter discussed in the manuscript.

Disclaimer: Any views expressed in this paper are those of the authors and do not reflect the official policy or position of the Department of Defense.