Fiber Reinforced Concrete (FRC) for High Rise Construction: Case Studies

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Abstract. Due to its material element, Fiber Reinforced Concrete (FRC) could be stronger than traditional Concrete. This is due to FRC internal material compounds and elements. Furthermore, FRC can also significantly improve flexural strength when compared to traditional Concrete. This improvement in flexural strength can be varied depending on the actual fibers used. Although not new, FRC is gradually gaining popularity in the construction industry, in particular for high rise structures. This is due to its flexural strength, especially for high seismic zones, as it will provide a better solution than reinforced Concrete. The main aim of this paper is to investigate the structural importance of FRC for the high rise construction. Although there has been numerous studies and literature in justifying the FRC for general construction; this paper will consider its use specifically for high rise construction. Moreover, this paper will closely investigate eight case studies from Australian and United States as a part of the FRC validation for high rise construction. In doing so, this paper will examine their Structural Health Monitoring (SHM) to determine their overall structural performance.

1. Introduction
Generally, composite materials are made up of individual constituents, including matrix and reinforcement [1]. Conversely, the matrix material surrounds and supports the reinforcement materials by maintaining their relative positions; and the reinforcements pass on their special mechanical and physical properties to enhance the matrix properties [2]. While the composite could be formed into various shapes, the matrix can be introduced to the reinforcement, before or after the reinforcement material has commenced being manufactured. [3].

Many commercially produced composites use polymer matrix material, often called a resin solution, as their matrix. There are many different polymers available, depending on the starting raw ingredients. The reinforcement materials are often fibers, but can also be commonly ground minerals. Figure 1 below shows fiber elements and the finished product.

![Figure 1. From raw fiber to finished material](image-url)
In construction and building structures, fiber reinforced modules are utilized as composite materials [4]. Fiber reinforced materials are unconventional materials, which utilize substances such as Fiber as bonding agents [1]. With every increase in material waste, the utilization of such bonding agents can also further reduce the impact of recycling requirements [5]. More importantly, such innovative materials, can withstand the required loads (stress and strain) as per more conventional methods of material engineering [6].

FRC is an example of such innovative material engineering. Although this material has been used in general construction for some time, its use for high rise construction is gradually increasing. In the past, the reason for the reluctant use of FRC for high rise construction was due to industry’s lack of trust with its functionality [7]. As per norm, material functionality is the most important factor to consider when a selection is being carried out [8]. One of the most significant facets of material functionality is its ability to fit the purpose which it is required to do. As per traditional Reinforced Concrete (RC), such materials are utilized as load bearing components of the structures. With the development of the FRC, it is believed that this material cannot match the functionality of the RC. However, many studies have been conducted to support the opposite to this view [8]. Furthermore, where low load bearing materials are required, FRC can easily be employed [9].

The intriguing aspect of FRC is the actual type of fiber which is being used as there are many fibers to select from, such as Polymer, Steel, Glass and even Natural fibers (vegetable origin) [10]. Figures 2a and 2b below illustrate Steel and Glass fibers.

Figure 2A. Steel Fiber [9].

Figure 2B. Glass Fiber [4].

Moreover, another important aspect of FRC is its composition progression, including the interface and bonding processes [9], both of which are discussed further in the following section.

2. FRC Composition Progression

As already discussed, Fiber Reinforced materials are unconventional materials, which utilize substances such as Fiber as bonding agents. The properties of the Fiber-Concrete interface have a critical effect on the properties of FRC [4]. Also as previously conversed, a key aspect of FRC is its composition progression, including its interface and bonding processes. While the bonding process includes the actual bond strength, the interface comprises of the actual cross point between quantities of fiber and concrete[11]. Table 1 (below) further depicts these two key processes.

| Processes   | Actions                                                                 | Effect                                                                 |
|------------|-------------------------------------------------------------------------|-----------------------------------------------------------------------|
| Interface  | Fibers such as steel create specific zones and boundaries where the actual interface is being created | Gradual mixing occurs: for example for glass Fiber it takes up to 28 days |
| Bonding    | The joining action will take place and its curing time depends on the Fiber type and the environment | Three types of bonding process can occur: elastic, frictional and mechanical |

As it can be observed, both processes are complex and subjective to many factors. More importantly, the bonding process can be achieved via three different processes [8]:
• Elastic, that is the Fiber sticking to the matrix.
• Frictional, which is creating friction and also providing resistance to pull out force. Frictional bonding controls the significant element of FRC stress-strain behavior, and highlights the cracking value and its subsequent performance [9].
• Mechanical, which ensures the fibers and their composition correctly interlock with the matrix. Of the three bonding process, mechanical is the most complex and complicated procedure. As Gharehbaghi (2015) correctly argued, crimping the fibers to provide the mechanical bonding can effectively increase the average bond stress value by an approximate "factor of four". Although there are many literatures discussing which method of bonding is more effective, as a general rule, the performance of the bonding is rather dependent on the actual fiber type, for example, steel, glass and so on [11]. Although the bonding process is a considerable issue to contemplate, ultimately it is the fiber type which could determine the structural performance of the FRC [12]. Determination of the structural performance is a vital issue to contemplate when considering the use of FRC for high rise construction.

3. FRC For High Rise
As outlined earlier, there is much literature regarding the use of the FRC for general construction. However, this paper highlights the importance of FRC specifically for high rise Construction. Figures 3a and 3b below exemplify the assembly and erection of FRC for high rise construction.

![Figure 3A. Retaining walls (for high rise) made from FRC.](image1)

![Figure 3B. Assembly of FRC panels.](image2)

While figure 3a illustrates retaining walls made from FRC together with connection bars as additional support; figure 3b demonstrates the assembly of FRC panels for high rise construction. Structural Health Monitoring (SHM), which refers to the process of implementing a damage detection and characterization strategy for buildings, is a key tool in determining the structural performance of the FRC for high rise construction.

4. Structural Health Monitoring (SHM)
In determining damage detection and monitoring of structures important techniques such as Structural Health Monitoring (SHM) are utilized [13]. The SHM technique ensures that effective monitoring of structures is carried out due to long-term movement and degradation of their materials [14]. Commonly, the main causes of deterioration in structures such as buildings include wear and tear together with additional movements [7]. For buildings in particular the main deterioration includes cracking due to significant structural loads consisting of Imposed and Seismic loads, together with the Environmental loads (including Temperature changes, and so-on). Moreover, a period of dramatic environmental changes, such as increased Seismic activities, could further complicate the SHM process and analyses; and also reduce the Building's structural performance [11].

As Gharehbaghi (2017) correctly claimed, the traditional damage detection strategies consist of visual inspection and localized non-destructive evaluation techniques, such as vibration and impact tests. Moreover, the utilization of Young’s modulus can further assist with determining any structural
deterioration and damage. An important aspect for FRC for high rise construction is to be sure that it maintains adequate structural integrity. Correspondingly, using SHM to be sure that FRC adequately meets the structural integrity is an important damage detection and monitoring consideration. In addition, SHM improves the functionality of building together with timely warning of impending failures, and thus will provide appropriate and cost-effective maintenance regimes [14]. To further examine the importance of the FRC for high rise construction, a case study of eight buildings from Australian and United States was conducted.

5. Case Studies
To systematically examine FRC for high rise construction, a case study consisting of a variety of high rise buildings was carried out. The status of each structure and its fiber information was captured and is shown in table 2 below.

| Structure      | Fiber Type | Fiber Bonding Process | Fiber Insertion |
|----------------|------------|-----------------------|-----------------|
| Building I     | Steel      | Mechanical            | Internal Walls  |
| (USA)          |            |                       |                 |
| Building II    | Steel      | Combination of Frictional and Mechanical | Internal Walls |
| (AUST)         |            |                       |                 |
| Building III   | Steel      | Combination of Frictional and Mechanical | Internal Walls |
| (USA)          |            |                       |                 |
| Building IV    | Polymer    | Mechanical            | External Walls  |
| (USA)          |            |                       |                 |
| Building V     | Steel      | Mechanical            | Internal Walls  |
| (AUST)         |            |                       |                 |
| Building VI    | Polymer    | Mechanical            | External Walls  |
| (USA)          |            |                       |                 |
| Building VII   | Steel      | Combination of Frictional and Mechanical | Internal Walls |
| (USA)          |            |                       |                 |
| Building VIII  | Polymer    | Mechanical            | External Walls  |
| (AUST)         |            |                       |                 |

As it can be noticed, most of the buildings utilized Steel as the basis of their FRC. In addition, their fiber bonding process generally consists of a combination of Frictional and Mechanical bonding. This is perhaps due to these two processes being the most commonly used in the material engineering fields. As a part of the Structural Health Monitoring and Modeling, SensorConnect provided all the necessary and up-to-date data for the analysis purposes. Figure 4 provides a SensorConnect output for one of the Buildings studied.
In addition, to further examine these structures, each building’s structural performance was analyzed using SensorConnect software, and their summary is shown in table 3 below.

**TABLE 3.** Comparison of SHM performance

| Structure | Structure Age (years) [approximately] | Imposed Loads | FRC Component | SHM Performance (Overview) |
|-----------|---------------------------------------|---------------|---------------|----------------------------|
| Building I (USA) | 8 | Intermediate Seismic | Non-load bearing | Outstanding and exemplary |
| Building II (AUST) | 15 | Standard | Non-load bearing | Due for a some minor upgrade and improvements |
| Building III (USA) | 21 | Minor Seismic | Non-load bearing | Due for a minor upgrade and improvements (some cracking due to movements) |
| Building IV (USA) | 9 | Standard | Limited load bearing | Outstanding and exemplary |
| Building V (AUST) | 11 | Standard | Non-load bearing | Satisfactory and on-going |
| Building VI (USA) | 7 | Standard | Non-load bearing | Minor structural failure (displacement) |
| Building VII (USA) | 18 | Minor Seismic | Non-load bearing | Due for a some minor upgrade and improvements |
| Building VIII (AUST) | 2 | Standard | Limited load bearing | The structure is too new to notice any wear and tear |

While the Structure age is only an approximation, it is important to note that all the buildings were Monocoque structures. This includes the involvement of additional structural reinforcement especially for demanding areas such as Seismic areas. Generally, FRC was utilized for non-load bearing structural components, especially for Seismic areas. As it can be noticed from table 3, the majority of buildings involved the use of Steel as the basis of FRC. The SHM process involved accessing the available and allowable database.
As already discussed the SHM technique involved:

- Using SHM logs to collect the sensor data from all the buildings and then analyzing the data on a high end platform.
- Accessing the maintenance and inspection logs to retrieve the periodic (depending on the inspection regimes) visual inspection records.
- Accessing the dedicated data-acquisition SensorConnect Software for sensor configuration and data collection.

As already discussed, as a part of the Structural Health Monitoring and Modeling process, SensorConnect provided all the necessary and up-to-date data for analysis purposes. This analysis further provided the information to be used for the SHM Performance column in the table 3 above. The SHM performance includes information about the overall structural health together with the performance of the buildings, including the observation of any maintenance and rehabilitation regimes and schematics.

6. Summary

The general principle of composite materials is to engineer materials which are stronger, lighter, and possibly less expensive when compared to traditional materials. In high rise construction, the composite materials usually include, concrete, and FRC among other materials. Much research has been conducted to demonstrate that due to its material elements, FRC is rather stronger than traditional Concrete. Although not novel, FRC is steadily gaining recognition in the construction industry in particular for high rise structures such as buildings.

Fittingly, the main aim of this paper was to investigate the structural significance and functioning of FRC for high rise construction. Although there has been abundant investigation into justifying the use of FRC for broad-spectrum construction, this paper provided a number of case studies (from Australia and United States) to further encourage its usage, explicitly for high rise structures.

Finally, this paper examined the case studies using SHM, to further emphasize their overall structural integrity. Close examination of the case studies found that all the buildings were Monocoque structures. This included the involvement of additional structural reinforcement particularly for demanding areas such as Seismic areas. Moreover, FRC was thus utilized for non-load bearing structural component, predominantly for Seismic areas.

7. References

[1] K. Gharehbaghi, Material Advancements for High-rise Construction (Proceedings of the 5th International conference on the constructed environment, University of Pennsylvania, Philadelphia, 16-17 October 2014).

[2] R. C. Hibbeler and K. S. V. Sekar, Mechanics of materials (9th edition, worldwide adaptation edition, SI edition, Singapore: Pearson Education South Asia Pty Ltd, 2014).

[3] M. S. Mamlouk and J.P. Zaniewski, Materials for Civil and Construction Engineers (3rd edition, Prentice Hall, London, 2011).

[4] J. Gustavo, High Performance Fiber Reinforced Cement Composites 6 (International RILEM conference on high performance fiber reinforced cement composition, 2012)

[5] F. Ching, Building structures Illustrated Patterns, Systems, and Design (2nd edition, Hoboken: Wiley, 2013).

[6] S. Goodhew, Sustainable construction processes: a resource text (Hoboken: John Wiley and Sons, 2016).

[7] K. Gharehbaghi, Advancements in Concrete Technology in Australia: Geo-Polymer Concrete (International Journal of the Constructed Environment, Vol 7, issue 1, pp 19-29, 2015).

[8] J. Gere, and B. Goodno, Mechanics of materials (8th edition, Stamford, Conn.: Cengage Learning, 2013).

[9] E. Cuerca, On Shear Bahavior of Structural Elements made of Steel Fiber Reinforced Concrete (Springer: USA, 2014).
[10] P. Domone and J. Illston, Construction Materials: Their nature and Behaviour (4th edition, Spon Press, London, 2010).

[11] P. Xincheng, Super-high-strength high Performance Concrete (Hoboken: Taylor and Francis, 2012).

[12] A. Ramdasi and N. Tande, Lateral load analysis of High Rise Structures (International Journal of Engineering Science and Technology, Vol 6, Iss 6, pp 268-275, 2014).

[13] H. Hugo, Performance Based Building Design 1 From Below Grade construction to Cavity Walls (Hoboken: Wiley, 2012).

[14] K. Gharehbaghi, Modular high-rise construction as an alternative building system, (international Journal of the Constructed Environment, Vol 8, Iss 3, pp 15-25, 2017).