This paper provides an overview of an ongoing research project at The University of Auckland that is investigating the potential of ductile fibre reinforced cementitious composites (DFRCC) as a structural material in New Zealand. A brief overview of international research on DFRCC is given, including an explanation of how DFRCC differs from conventional fibre reinforced concrete. Researchers at The University of Auckland have begun mixing trial batches of DFRCC, and this paper gives some results from this investigation, along with comments about experience obtained from mixing these trial batches. To date DFRCC has not been successfully produced, although tensile properties of the concrete are significantly better than plain concrete. Finally, details are presented of an innovative method of constructing equivalent monolithic moment resisting frames using DFRCC connections to join precast concrete beam and column elements.

INTRODUCTION

Concrete is generally considered to be a material that has excellent properties when strained in compression and poor properties when strained in tension. To overcome this weakness, concrete used for structural purposes is normally enhanced with a material that has superior tensile properties. Such composite materials are referred to as reinforced concrete.

Traditionally the term reinforced concrete has been applied to concrete containing discrete steel elements placed to resist specific design actions, typically shear and flexure. More generally, the term reinforced concrete can refer to a number of other composite materials. For instance, it is possible to use materials other than steel as discrete reinforcing elements. An example of this is the increased use of fibre reinforced polymer (FRP) in concrete structures.

A further concept that falls under the heading of reinforced concrete is the use of fibres in concrete.

FIBRE REINFORCED CONCRETE

The use of randomly orientated fibres to improve the properties of concrete was pioneered by Romualdi and Mandel in the early 1960’s [1]. They showed that adding relatively small volumes of discontinuous steel fibres dramatically increased the cracking strength of concrete and allowed the concrete to resist tensile forces even after cracking.

Since this first research was undertaken, countless investigators around the world have demonstrated that the addition of steel, glass, synthetic or natural fibres to concrete can have one or more of the following effects on concrete [2]:
- increase tensile stress and strain capacity;
- improve impact resistance;
- improve flexural fatigue behaviour;
- increase toughness;
- provide a means of limiting crack width.

Strain Hardening Fibre Reinforced Concrete

When subjected to tensile stresses typical fibre reinforced concretes (for example a steel fibre reinforced concrete containing 2% fibres by volume) exhibit tension softening behaviour, that is the occurrence of peak stress coincides with the formation of the first crack. After cracking has occurred the stress that can be transmitted across the crack by bridging fibres is lower than the stress that can be sustained by the matrix material (concrete). This behaviour is shown in Figure 1 (a). While the tensile behaviour represented by this curve is superior to that of unreinforced concrete, it is likely to lead to highly localized damage in structures, particularly those subjected to earthquake induced forces.

Li & Leung [3] observed that some fibre reinforced concrete types reported in the literature (such as slurry infiltrated fibre concrete (SIFCON) with very high fibre volume) exhibited stress-strain responses that differed from the typical tension softening response. By investigating the micro mechanisms of cracking in fibre reinforced concrete they were able to explain the four possible families of stress-strain curves as shown in Figure 1.

1 Postgraduate Researcher, The University of Auckland
2 Associate Professor, The University of Auckland
Figure 1(a) shows the common tension softening response, while Figure 1(b), (c) and (d) show stress-strain responses where the crack bridging fibres exhibit strain hardening characteristics.

Li & Leung [3] showed that fibre composites could be found in the literature that exhibited all four of these stress-strain responses, and also showed that the stress-strain behaviour of a composite could be chosen at the design stage by tailoring the properties of the fibres and matrix material used. A key finding of their research was that for any combination of matrix and fibre, a critical fibre volume fraction can be determined. Composites with fibre volume fractions below this critical value will behave in a “traditional” tension softening manner; composites having fibre volume fractions greater than the critical value will display some form of strain hardening behaviour. For typical steel fibre reinforced concrete the critical fibre volume is approximately 4.0% [3], explaining why SIFCON can exhibit strain hardening while common steel fibre reinforced concrete does not.

By manipulating material properties of both the matrix and fibres used, Li and colleagues were able to develop cementitious composites that achieve desirable physical properties with relatively small quantities of fibres: this has obvious advantages in economic terms, and makes the material more workable.

The tensile stress-strain response of the most desirable category of fibre composites is similar to Figure 1(d). When a tensile stress is applied to such materials, a crack forms when the stress exceeds the cracking stress of the matrix material ($\sigma_{fc}$). Since the fibres bridging this crack can sustain the tensile stress applied, there is no strength loss after crack formation. As the load applied continues to increase, further cracks form at small regular spacings. This distribution of cracking allows significant overall deformation to occur while limiting the opening of individual cracks. Crack opening is controlled until the stress the must be transferred across a crack exceeds the maximum strength of the bridging fibres ($\sigma_o$).

Fibre reinforced cementitious composites that exhibit tensile strain hardening have been given a number of names around the world, including:

- High Performance Fibre Reinforced Cementitious Composites (HPFRCC);
- Engineered Cementitious Composites (ECC);
- Ductile Fibre Reinforced Cementitious Composites (DFRCC)

The use of these names appears to be geographically based. In this paper the name DFRCC will be used, as it is the opinion of the authors that this name is both the least ambiguous term and the most descriptive of the properties of the material.

While DFRCC can be produced that has very high compressive and/or tensile strength, these are not considered to be its defining characteristics. Rather, the property that distinguishes DFRCC from other high performance concretes is its tensile strain capacity, which can be as large as 5-6%, i.e. more than two orders of magnitude greater than conventional plain or fibre reinforced concrete [4]. The ability to tailor the properties of DFRCC by material selection is illustrated in Figure 2 (taken from [5]), which shows the tensile stress-strain response of different cementitious composites. PC and FRC refer to plain concrete and a normal tension softening fibre concrete respectively. DRECC and SPECC are two different types of DFRCC containing steel and polyethylene fibres and optimised for strength or strain capacity respectively.

When used in structures or structural components DFRCC has been shown to have numerous
advantages over more traditional materials. These include [4]:

- reduction or elimination of conventional shear reinforcement;
- ability to sustain large deformations without damage/deformation concentrating at a single crack;
- reduced reliance on bond strength due to the ability of DFRCC to transmit tensile stresses even after cracking has occurred;
- improved tolerance to damage (e.g. notching) and stress concentration;
- elimination of spalling even when very large cyclic deformations are imposed on a structure.

These advantages translate particularly well to structures expected to be subjected to severe cyclic loading (for example see Figure 3) and where high shear demands are expected, such as in coupling beams (see Figure 4 taken from [6]).

**Applications of DFRCC**

Although DFRCC is a relatively recent invention, it has been used for a number of different purposes internationally. Some of these are summarised by Li [7]:

- repair of dams;
- repair of retaining walls;
- in the replacement of bridge expansion joints with ductile link slabs;
- creation of a thin composite deck for a newly constructed cable stayed bridge in Japan.

**Ductal and DFRCC**

It should be noted that Ductal® [8] can be considered to be a DFRCC. Ignoring differences in flexural strength and other physical properties (which are purely a function of choices made at the material design stage) the significant difference between Ductal® and generic DFRCC is that Ductal® is a proprietary product while DFRCC in general describes a class of materials designed according to openly published principals [3].

**PRELIMINARY INVESTIGATIONS OF THE PROPERTIES OF DFRCC**

While DFRCC has been the subject of significant amounts of research internationally, there appears to have been no local investigation of the potential of DFRCC in New Zealand. In order to gain experience mixing DFRCC, and to try and determine whether using New Zealand materials affects the performance of DFRCC based on mix designs developed overseas a number of small batches of polyvinyl acetate (PVA) fibre concrete have been produced at The University of Auckland. Test beams and cylinders manufactured from these mixes have been tested and results are presented in this section.

**Material Properties**

The key component of a DFRCC is the fibre used. The fibre selected for this study was Kuralon RECS15/8, a PVA fibre designed specifically for use in DFRCC and produced by Kuraray. Physical properties of the fibre are shown in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Length</th>
<th>Diameter</th>
<th>Tensile Strength</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>mm</td>
<td>MPa</td>
<td>GPa</td>
</tr>
<tr>
<td>PVA</td>
<td>8</td>
<td>0.04</td>
<td>1600</td>
<td>40</td>
</tr>
</tbody>
</table>

The mix design used was initially based on a mix received from Kuraray, which is shown in Table 2. Note that the absence of coarse aggregate in the mix is typical of DFRCC.

Since one aim of these test mixes was to determine the suitability of New Zealand materials
for use in DFRCC, sand, cement and flyash were obtained from Golden Bay Cement and were not specifically prepared in any way. The super plasticiser used was Glenium 51, supplied by Degussa Construction Chemicals NZ. 26 kg/m$^3$ of PVA fibres were added to the mix, equating to a volume fraction of approximately 2.0%, again typical of DFRCC.

Table 2 Kuraray mix design for PVA DFRCC

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity</th>
<th>kg/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Flyash</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>Super plasticiser</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Fibres</td>
<td>26</td>
<td></td>
</tr>
</tbody>
</table>

A number of test mixes were produced, and for later mixes minor alterations were made to the mix design based on experience gained from early mixes. The main change made was to reduce the water to cement ratio from 0.44 (Table 2) to 0.37 in steps. This was done as the initial mixes produced a large amount of bleed water (see Figure 5).

Comments on Wet Mix

There appears to be a perception that fibre reinforced concrete (in particular steel fibre reinforced concrete) is a difficult material to work with. In contrast, PVA DFRCC is a very easy material to work with. The fibres used are soft, and no special precautions need be taken when handling them. Furthermore, when DFRCC is mixed as described by Table 2 (i.e. a volume fraction of 2.0%) the mix is quite flowable, and hence very easy to place. As mentioned the water/cement ratio was reduced in later mixes. This reduction had no notable effect on the workability of the concrete.

A property common to all of the mixes was the occurrence of a large amount of volume change during curing (see Figure 5). Although not measured accurately, hardened concrete cylinders typically had a height of 195 mm, despite standard 200 mm tall moulds being filled completely during casting.

To investigate the effects of adding more than 2.0% fibres to the mix, a trial mix containing 3.0% fibres by volume was produced. This mix was extremely difficult to prepare and place. The effect of the added fibres on the properties of the hardened concrete was negligible. This may be partly due to the difficulties encountered in placing the material in moulds.

Figure 5 Bleed water and volume change of DFRCC concrete cylinders 24 hours after casting

Measurement of Physical Properties

Two categories of tests are commonly used to assess the tensile properties of DFRCC. These are uniaxial tensile tests and bending tests. To date there has been no agreement on a common testing standard. Some suggest that fibre composites cannot be accurately classified as ductile or non-ductile without direct tension tests being conducted [9, 10], while others suggest that the complexity and variability of uniaxial tension tests makes such tests impractical as a standard test method [11].

As a means of obtaining preliminary information about the tensile properties of fibre composites mixed at the University of Auckland, a simple four point bending test was selected. Two beam sizes were tested. The smaller beams had cross section dimensions of 50 mm square and a length of 300 mm, while the larger beams had cross section dimensions of 100 mm square and a length of 500 mm.

In addition to the tensile tests, compressive strength was measured by testing concrete cylinders.

Test Results

The compressive strength of the fibre composites produced at The University of Auckland was measured by crushing standard test cylinders. Cylinders were crushed after 7 and 21 days. Table 3 shows the average compressive strengths of the mixes. It can be seen that all mixes had developed similar strengths by an age of 21 days, with the fourth mix developing a slightly higher strength, probably due to the use of more cement in the mix.

A total of 24 small (50 mm square cross section) and 8 large (100 mm square cross section) flexural beams were tested. Representative force-displacement curves are shown in Figure 6.
Multiple distributed cracking did not occur in any of the beams tested, indicating that the fibre composites used had a tension softening behaviour rather than a strain hardening behaviour. A beam showing typical damage is shown in Figure 7. The plots that comprise Figure 6 show signs of ductile behaviour, with significant deflection occurring without a loss of strength after cracking. However, this behaviour is likely to be a structural property rather than a material property. The small size of the beams tested means that ductility can be obtained even if the material has a tension softening response [10].

Table 3 Compressive strength of DFRCC mixes

<table>
<thead>
<tr>
<th>Water/cement ratio</th>
<th>Compressive strength at 7 days</th>
<th>Compressive strength at 21 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.43</td>
<td>MPa</td>
<td>41.3</td>
</tr>
<tr>
<td>0.40</td>
<td>46.0</td>
<td>55.1</td>
</tr>
<tr>
<td>0.37</td>
<td>45.3</td>
<td>54.3</td>
</tr>
<tr>
<td>0.37*</td>
<td>50.6</td>
<td>58.8</td>
</tr>
</tbody>
</table>

* altered mix design, with 660 kg/m$^3$ of cement and 560 kg/m$^3$ of flyash.

Despite not having the desired strain hardening behaviour, the fibre composite beams had considerably more strength than would be expected from beams made from plain concrete with similar compressive strength. The strength that would be expected of plain concrete beams with similar compressive strength was calculated for each of the 32 beams tested, assuming a modulus of rupture of $0.6\sqrt{f_c}$ as specified by NZS 3101 [12]. On average, the fibre reinforced beams were 2.84 times stronger than the calculated value. Although there was some scatter amongst the strengths of the fibre reinforced beams, all beams had at least twice the strength that would be expected of a similar plain concrete beam.

The reason that the PVA fibre composites produced at The University of Auckland have not yet exhibited strain hardening, multiple cracking behaviour is not completely clear. The most likely answer seems to be that the toughness of the matrix material is too high. This has the effect [3] of increasing the critical fibre volume fraction required to achieve strain hardening behaviour.

**REINFORCED CONCRETE BEAM-COLUMN JOINTS**

The seismic performance of reinforced concrete moment resisting frames is strongly influenced by the design and construction of the beam-column joints incorporated in the frame. Joints must be designed to resist large shear forces and should have sufficient depth to prevent bond failure from occurring [13].

It is generally accepted that beam-column joints designed according to modern standards such as NZS 3101 [12] should perform very well if subjected to a large earthquake. However, this excellent performance generally requires beam-column joints that are heavily congested with reinforcement (see Figure 8) including numerous beam longitudinal bars to ensure the ratio of column depth to bar diameter is sufficient to prevent bond failure and large amounts of transverse reinforcement [13]. It has long been
desired to find a solution to this reinforcement congestion.

Figure 8 Reinforcement congestion in a typical beam-column joint

**Fibre Reinforced Beam-Column Joints**

One potential solution to joint congestion that has been investigated by numerous researchers is using fibre reinforced concrete to reduce or eliminate the need for joint shear reinforcement [14-25]. These investigators have shown that fibre reinforcement (particularly with steel fibres) can improve the performance of beam-column joints. However, in joints where all conventional shear reinforcement is eliminated from the joint, damage localisation tends to occur after diagonal cracking of the joint region and is accompanied by a significant reduction in stiffness. This loss of stiffness is generally considered to be undesirable in a seismic resistant structure. Only in joints with a combination of fibres and conventional reinforcement was the performance found to be comparable to conventionally detailed joints.

A much more successful type of fibre reinforced beam-column joint was tested by Parra-Montesinos et al. [26]. The core region of these joints was constructed from a DFRCC containing polyethylene fibres, and contained no conventional shear reinforcement. Under reversed cyclic loading the joints exhibited stable hysteretic performance to drift levels of at least 5.0%. In addition, the bond performance of the joint region was excellent despite the ratio of beam longitudinal bar diameter to column depth being very high. It was concluded from these tests that no conventional shear reinforcement would be required in beam-column joints constructed from DFRCC.

**Precast Concrete Beam-Column Joints**

Construction using precast concrete is extremely popular in New Zealand, primarily because of the potential to:

- reduce construction time and cost;
- reduce the need for skilled labour on site and;
- increase the quality of concrete structures.

A key feature of using precast concrete is the need to connect individual elements to create a functional structure. To create precast concrete frames in New Zealand, elements are normally connected in ways that cause the finished structure to behave similarly to an in-situ concrete frame. Such connections and structures are described as equivalent monolithic, and a number of solutions have been developed and tested previously [27, 28]. Three of the most commonly used connection configurations are shown in Figure 9.

Figure 9(a) Precast beams connected at joint region (after [28])

Figure 9(b) Precast beams through columns, beam connection at mid-span (after [28])

Figure 9(c) Precast tee or cruciform units (after [28])
While there is no doubt that the connections shown in Figure 9 behave as expected [27] it was hypothesised that developments in materials technology may allow simpler construction methods to be developed.

**PRECAST BEAM-COLUMN JOINTS USING DFRCC**

Two precast beam-column joint sub-assemblies have been constructed at the University of Auckland that will provide initial data on the performance of a new method of assembling equivalent monolithic precast concrete moment resisting frames. The key features of this system are listed below:

- placement of in-situ connection in the beam-column joint region, allowing compact precast components to be utilised (i.e. the system does not require the use of tee or cruciform shape precast elements);
- termination of top and bottom beam longitudinal reinforcement at the beam-column joint region, simplifying transport and construction;
- use of DFRCC in the beam-column joint region, removing the need for transverse reinforcement in the beam-column joint and thus simplifying reinforcement fabrication.

An assembled beam-column joint sub-assembly is shown in Figure 10. Figure 11 shows the precast elements used to assemble this joint. Key features are the termination of the beam longitudinal reinforcement in a “U” bend, and the void left in the column at the joint core. It is recognised that this column design would be impractical in a real structure, and that the column would likely include a connection in the vicinity of the joint core using grout sleeves or a similar method. It was felt unnecessary to include this type of connection in the initial test units, as grout sleeves are a well proven technology.

Figure 10 Assembled precast beam-column joint sub-assembly

Figure 11 Precast beam-column joint elements

Figure 12 Plan view of joint region - transverse reinforcement omitted for clarity

The design of the two initial beam-column joints was based closely on the requirements of NZS 3101 [12]. It is likely that a number of aspects of these joints will be conservative, in particular the expected level of joint shear stress and the anchorage length provided for the beam longitudinal reinforcement. Based on the results of these first tests (to be presented at conference) it is planned to design and test a series of beam-column joint sub-assemblies where key parameters are varied, enabling design recommendations to be formulated.

Figure 13 shows a beam-column joint under construction using the method proposed here.
CONCLUSIONS

Ductile fibre reinforced cementitious composites are an innovative class of materials that have the potential to significantly improve the performance of reinforced concrete structures if applied appropriately. While unlikely to be suitable for use as a direct replacement of conventional concrete, they offer significant improvements to the performance of elements expected to be subjected to large cyclic deformations or significant shear demands.

DFRCC can be tailored to provide desirable physical properties such as high tensile strength or high tensile strain capacity by the application of openly published micro-mechanical principles [3].

A pilot program conducted at The University of Auckland to produce PVA DFRCC using New Zealand materials has not yet been successful, although significantly greater strength was developed by fibre reinforced flexural beams tested than would be expected from plain concrete beams with similar compressive strength. PVA fibre reinforced concrete has proven to be an easy material to work with.

It is intended to continue efforts to create DFRCC in New Zealand, and to use this material in a proposed method for connecting precast concrete elements to create moment resisting frames.

REFERENCES


