The Use of FBG Sensor to Determine the Fracture Energy Properties of UHPFC

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Abstract. This paper discusses the results of an experimental investigation on the fracture properties of Ultra-High Performance Fiber Reinforced Concrete (UHPFC), using fiber optics brag grating, FBG, strain gauges rather than the conventional mechanical accelerometer. FBG sensors are one of many fiber optic sensor technologies that are currently being used in structural health monitoring systems. The sensors operate by detecting a shift in the wavelength of the reflected maximum due to applied strain. Structurally, each conventional strain gauge has two wires serving as input and output ports respectively, unlike fiber Bragg grating based sensors where several sensors can be multiplexed onto the same optical fiber. Consequently, FBG sensors could allow for a larger and a more accurate measurement for the fracture and cracking response of concrete members. The fracture energy, G_F, is defined as the area under the stress-strain curve per unit fractured surface area, is experimentally determined for the UHPFC. Fracture energy is important in determining design parameters such as shear strength and tensile strength, obtained by the work-of-fracture method, and is used in the development of models useful in engineering practice.

1. Introduction

Ultra High Performance Fiber Reinforced Concrete, referred to as UHPFC henceforth, is the name given to a class of materials that exhibits properties superior to those of conventional concrete. Numerous researches have been conducted to determine the structural behavior of concrete. Many authors suggest the fracture characteristics of concrete are of upmost importance. Consequently, the fracture energy, G_F, tensile strength, f_t and the stress-CMOD relationship completely describes the fracture characteristics of concrete [1]. Tensile strength of concrete is an essential property, though it is not directly used in design calculations for normal and high strength concrete. Nevertheless, not only is the tensile strength is important also the tensile fracture behavior is of significance value for fiber reinforced concrete. One way of quantifying fractural behavior of concrete is by means of fracture energy.

The fracture energy, G_F, is defined as the area under the load-CMOD curve per unit fractured surface area [2].Researchers have advised, unlike other materials, energy absorbed by concrete members in tension is associated with the descending portion of the stress-displacement curve. A significant fractural parameter of concrete is the characteristic length, l_{ch}, though it has no physical meaning it is a representation of material properties such as modulus of elasticity E_c; tensile strength f_t' and fracture energy, G_F, [3]. A high value of l_{ch} represents concrete that is less brittle.

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The brittleness behavior of concrete, made it almost impossible to capture the fracture energy of concrete due to the sudden failure under flexural stresses. However, when using UHPFC it is expected, due to the fiber matrix, that an inelastic strain-hardening region exists. The region between the ends of linear elastic range and the peak load denoted, region II, in Figure 1 is a result of multiple micro cracking. The linear elastic region, region I, represents the micro cracking stage. The softening stage, region III, corresponds to the single failure crack opening and is mainly controlled by the fiber pulling-out process [4].

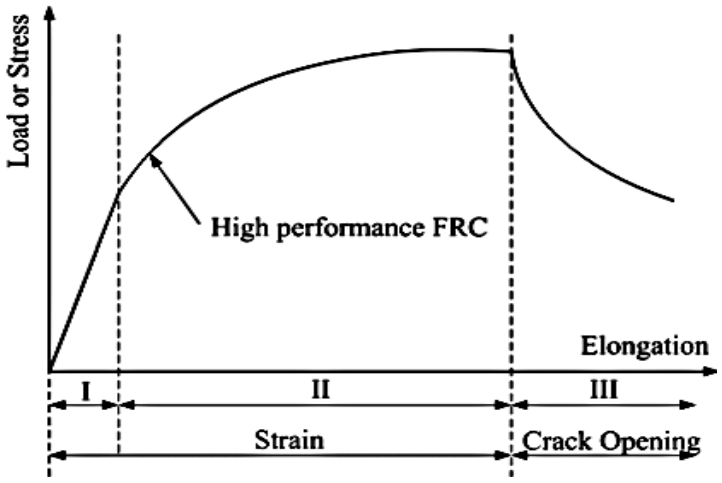


Figure 1: Stress-Strain Relation for UHPFC (Martin & Stanton, 2007)

2. Experimental Procedure

2.1 General

High strength concrete, HSC, as we know it today is a result of ongoing research and invention dated back to at least 30 years ago. It is widely used all over the world and is not limited to North America. A new versatile material, UHPFC possesses desirable properties including strength, ductility, durability and aesthetic design flexibility that are far superior to those of HSC. UHPFC is specified where reduced weight is important or where architectural considerations require small load carrying members.

Ductal©, a family of UHPFC designed by Lafarge North America provides a unique combination of superior properties (strength, durability, ductility and aesthetics) due to an integrated fiber matrix with low porosity from a combination of fine raw materials selected for their optimized size distribution and chemical characteristics. With improved resistance to abrasion, chemical resistance, freeze-thaw, carbonation and chloride ion penetration, Ductal is well suited for construction in aggressive environments. Ductal possesses superior material and structural properties when compared to normal and high strength concrete. Table 1 summarizes the general mechanical properties of Ductal Concrete as specified by Lafarge Canada [5].

Table 1: Mechanical Properties of Ductal Concrete (Lafarge North America)

Density	2500kg/m3
Compressive Strength on 75x150 cylinders	150-180 MPa
Direct Tensile Strength	8 MPa
Young's Modulus	50 GPa
Poisson Ratio	0.2

2.2 Test Specimens Preparation and Testing

The mixing procedure was conducted according to Lafarge North America specification for producing Ductal concrete. For confidentiality reason, the mixing procedure and proportions cannot be specified within the paper. Following the mixing, the concrete was then transported, in plastic buckets, to be casted in wooden molds previously prepared. The molds constructed had dimension of 200 x 300 x 1000 mm. prior to casting, an artificial notch, a_0=40mm, was prepared. In addition, to measure the strain along the fracture zone, a fiber optic strain gauge, 150 mm, was installed. Below is the specification of the constructed beams, Figure 2.

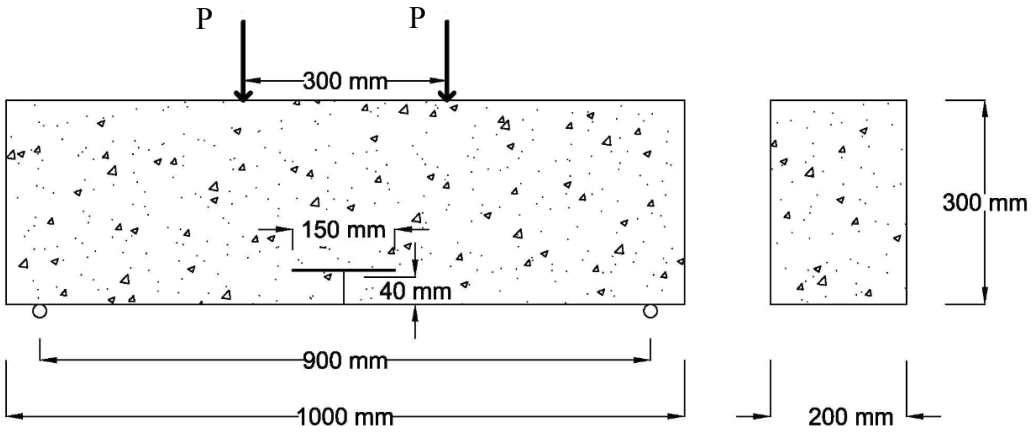
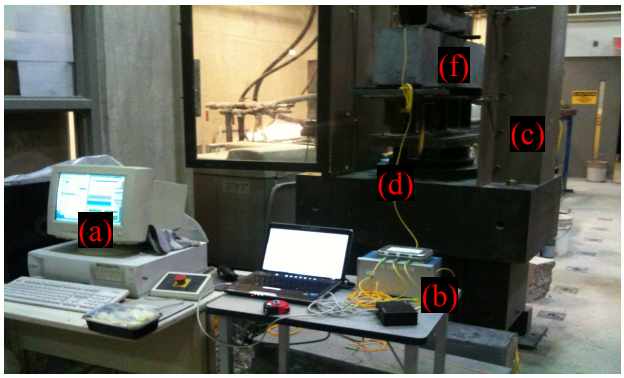


Figure 2: Test Beam Specifications

Literature review suggests strain or deflection control loading rate to correctly capture the fracture energy of concrete [3]. MTS testing machine used to apply the load in this experiment is capable of load, strain and deflection loading rate. As for the strain measurements a separate acquisition system was used to capture the change in wavelength from the fiber optics cable, with a gauge length of 150mm, which then can be used to calculate the strain along the cable. Both acquisition systems we programed to record measurements four times per second. Figure 3 below shows the experimental test setup. The experiment was conducted at a displacement rate of 0.0004 mm/s. Based on the results and the behavior observed from FE2, the loading rate was increased to, 0.008 mm/s, as it became evident a slow rate is not required due to the ductility of the test specimens due to the presence of the steel fibers.



(a) MTS acquisition system

(b) Fiber optic wavelength acquisition system

(c) MTS machine

(d) Fiber optics cable

(f) Test specimen

Figure 3: Test setup and instrumentation

3. Test Results and Discussion

In general, concrete is a brittle material thus making the capturing of complete load-deformation graphs a problematic task. Usually, a portion of the descending curve is captured then projected to produce a complete load-deformation curve. However, when using UHPFRC, the addition of the steel fiber matrix allows the concrete to behave with a more ductile property. Consequently, the load-deformation is easily captured. Figure 4 and 5 below; show the load strain relationship of the test beams FE1 and FE2. As shown in Figure 4, the load strain increased proportionally up to approximately 90% of the ultimate load f_u. Afterward, the strain increased dramatically while a minor increase in the load was observed, explained by the addition of the steel fibers present.

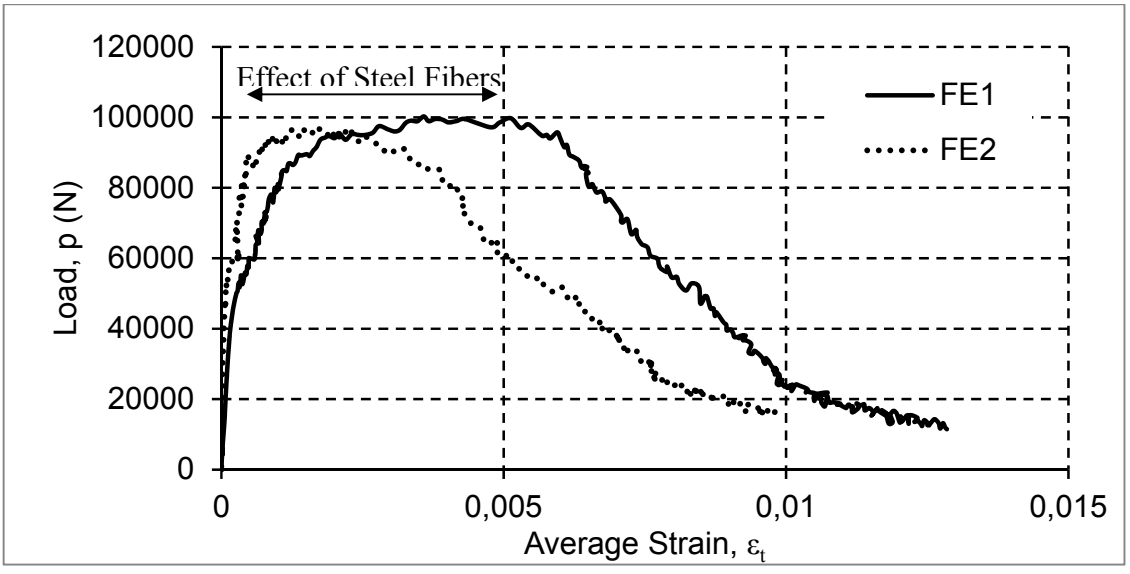


Figure 4: Average Tensile Strain Measurements of Beams FE1, FE2

In both of the tested beams, surface cracks were observed at approximately 80-90 % of the ultimate load. Subsequently, the strain gradually increased corresponding for crack opening, as the load decreased. However, internal cracks formed far before reaching the 80-90% of the ultimate load stage. These, internal cracks, would immediately propagate to the surface in the case of normal or high strength concrete. Nevertheless, one of the main advantages of using UHPFRC is that cracks are sealed and held tightly by the steel fibers present in the concrete mix.

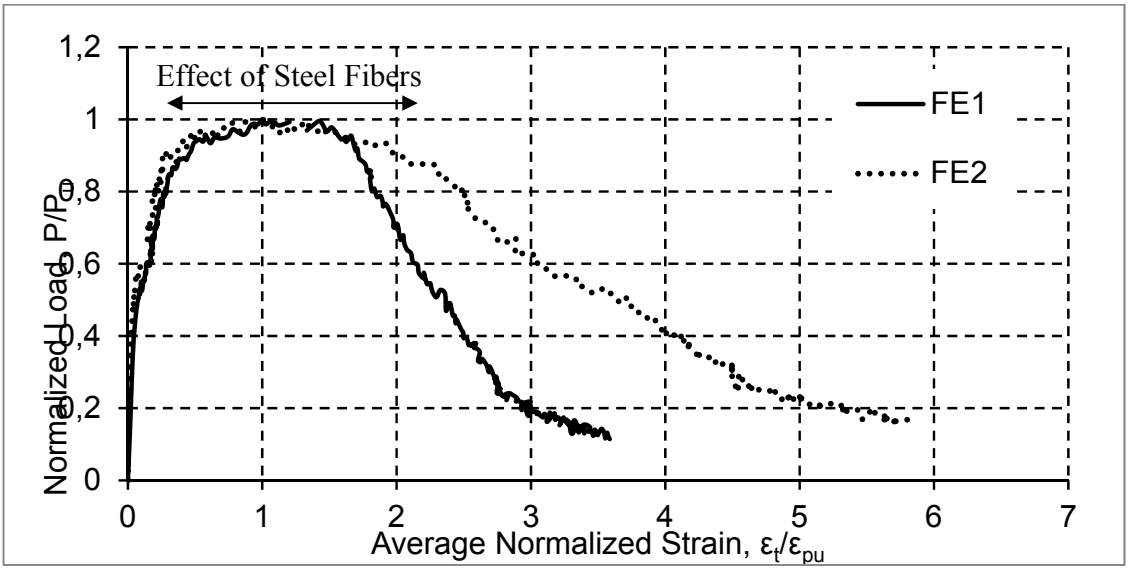


Figure 5: Average Normalized Strain Measurements of Beams FE1 and FE2

3.1 Fracture Energy

Fracture energy is the energy required to form a unit area of crack surface [6]. Many researchers suggest that the fracture energy of concrete be treated as a material property. Fracture energy, G_F is considred to be the area under the stress strain-curve. However, when dealing with concrete, unlike metal, the energy absorbed by conctere is only assoiated with the area under the decending portion of the stress-strain curve [3]. It must be noted that the effect of the steel fiber must also be included in the fracture energy, as it ultimalty gives UHPFRC it high compressive strength and tensile strength which are prameters that affect the fracture energy.

The maximum effective strain, ε_{max}, for HSC is reported to be around 16 times $\varepsilon_{p,}$ strain at ultimate load [3]. However, when using UHPFRC it is observed that ε_{max} is 4-6 times greater than ε_p. The fracture energy can then be claculated using the load-deformation response using Eq1 [7].Table 2 summarizes the mechanical properties of the test specimens.

[1] $G_F = (0.75W_0 + W_1)/A_{lig}$

Where,

G_F = fracture energy (N/mm)
$W_1 = 0.75(Sm_1/L + 2m_2)*g*CMOD_c$
W_0 = area below CMOD curve up to rupture of specimen (N.mm)
W_1 = work done by deadweight of specimen and loading jig (N.mm)
A_{lig} = area of broken ligament ($b*(h-a_0)$) (mm^2)
m_1 = mass of specimen (kg)
S = loading span (mm)
L = total length of specimen (mm)
m_2 = mass of jig not attached to testing machine but placed on specimen until rupture (kg)
g = gravitational acceleration (9.807 m/s^2)
$CMOD_c$ = crack mouth opening displacement at the time of rupture (mm)

Table 2: Mechanical Properties of UHPFRC

Specimen Name	f_c' (MGa)	f_u (kN)	ε_p x 10^{-6}	G_F (N/m)	E_t (GPa)	f_r' (MPa)
FE1	163	100.25	3500	1483.94	18	8.68
FE2	137	97.5	1700	1585.24	57	8.44

In general, fracture energy increases with the increases of the maximum coarse aggregate size. Howeve, such an observation can not be applied to UHPFRC since there is no coarse aggregate present. One,could make the argument of the fiber content having a signicicant affect on the fracture energy. The fber content has a significant effect on the load-CMOD graph; increasing the CMOD values significntly to those of normal or high strength concrete. The fracture energy of, G_F, of normal and high strength concrete, based on a directr tension test, are 110 N/m and 160 N/m respectively (Marzouk & Chen, 1995). This effect of the fibers is reflected in the high fracture energy values, Table 2. Its observed that UHPFRC yield fracture energy values that are much greater than those of normal and high strengh concrete.

3.2 Characteristic length

Characteristic length, l_{ch}, is a material property representing the size of the fracture zone. It expresses the fracture properties of concrete such as the modulus of elasticity, E_c; fracture energy, G_F; and tensile strength, f_t, where f_t is the direct tensile strength of concrete, as determined by the direct tension test [6] and is represented by Eq 2. While, l_{ch}, has no physical meaning; it act as a representation of the brittleness of concrete, the higher the l_{ch} value the less brittle the concrete.

[2] $l_{ch} = E_c G_F / f_t^2$ (mm)

Given the difficulties associated with fracture energy determination of concrete, researches have proposed empirical equations to predict the characteristic length using the compressive strength of concrete, Eq 3 [8] and [9].

[3] $l_{ch} = 600(f_c')^{-0.3}$ (mm)

[4] $l_{ch} = -3.84f_c' + 580$ (mm)

Table 3, below shows a comparison between chractristic length, derived from fracture energy Eq 2, and avilable models, Eq 3 and 4. In general it is understandable that the brittleness of concrete increases with the increase of compressive strength. Available models, Eq 3 and 4, follow that thearoy. The models available do not accurtly predict the chractristic length of concrete when compared to vlaues drived from Eq 2. However the models are conservitive, yeilding values resulting in a higher brittleness assumption. Needless to say, UHPFRC does not follow that trent. The significantly increased strength suggest a very brittle material, however the addition of the fiber matrix results in otherwise a very ductile material. Consequenlty, resulting in inaccurate l_{ch} values. This behaviour is also demenostrated in the fracture behaviour of the test beams, Figure 6. Typically, in conventional concrete with no reinforcement, a crack results in a sudden failure. However, in UHPFRC, as seen in Figure 6, the test beam remian intact even after crack propogation to the surface.

Figure 6: Crack Development During Testing of FE1

Table 3: Characteristic length of Concrete Ranging from 40-165 MPa

compressive strength (MPa)	l_{ch}, Eq2 (mm)	l_{ch}, Eq3 (mm)	l_{ch}, Eq4 (mm)
40	500	198.39	426.4
55	742	180.31	368.8
57.8	532	177.65	358.04
58.7	489	176.83	354.59
61	649	174.80	345.76
63	503	173.12	338.08
74	478	164.96	295.84
75	394	164.29	292
137	231	137.13	53.92
163	693	130.16	-45.92

4. Applications of Fracture energy

While the fracture energy is not directly used in the design of concrete structures, significant studies have been conducted to incorporate the fracture energy and behavior. Though it is not a representation of any physical property, l_{ch}, represents the brittleness of concrete. Numerous researches have gone into incorporating the characteristic length into design equation. For concrete beams without stirrups a model was developed by the Rilem Technical Committee represented by Figure 7, where f_v is the shear strength, f_t' is the direct tensile strength, d is the depth of the beam and ρ is the flexural reinforcement and l_{ch} is the characteristic length [6].

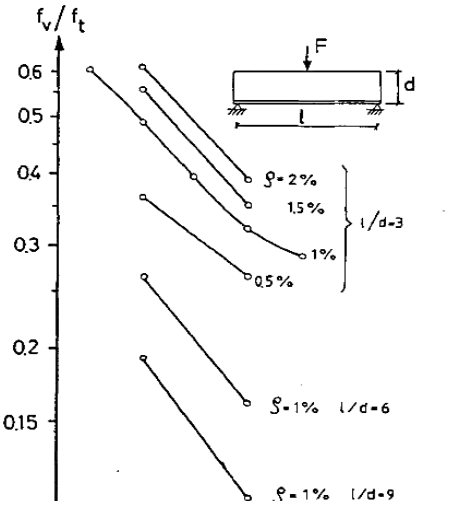


Figure 7: Theoretical Shear Strength of Reinforced Concrete Beams Without Shear Reinforcement (Hillerborg A. , 1985).

A later model was developed for shear strength of high strength concrete slabs represented by Eq 5 where c is the length of a side of a square column, d is the effective depth of slab, h is the total slab thickness, f_t is the uniaxial tensile strength of concrete and l_{ch} is the characteristic length [10].

$$[5] \quad v_u = 0.88\, f_t \left(\frac{c}{d}\right)^{-0.4} \sqrt[3]{\rho \frac{l_{ch}}{h}}$$

In design equation it is generally assumed that the shear strength is proportional to the tensile strength of concrete. However, many researchers argue, the use of the square root of the compressive strength to represent the tensile strength of concrete is not adequate when using HSC, HPC or UHPFRC. Hence, a major advantage is to incorporate the fracture energy within design equations.

5. Conclusion

UHPFRC, exhibits superior qualities compared to normal and high strength concrete. The introduction of fiber reinforcement proves to increase, significantly, the ductility of the mix; resulting in a concrete material that behaves rather different than conventional concrete. High strength concrete has a more brittle behavior to that of normal strength concrete, demonstrated by the sharp descends in the stress-strain curve. UHPFRC exhibits a far more ductile behavior when compared to normal and high strength concrete. This ductile behavior and the increased strength ultimately result in concrete with significantly higher fracture energy, consequently a higher characteristic length.

6. References

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