Dependence of fracture size effect and projectile penetration on fiber content of FRC

Zdeněk P Bažant, Mohammad Rasoolinejad, Abdullah Dönmez and Wen Luo
Northwestern University, Evanston, IL USA
E-mail: z-bazant@northwestern.edu

Abstract. The microplane constitutive model M7f for fiber reinforced concrete (FRC), previously calibrated by extensive material test data, is used in computational simulations of the size effect in geometrically similar notched specimens, and in simulations of penetration of projectiles into FRC targets. The M7f microplane model for fiber reinforced concrete is calibrated at the material level and then used to predict structural level behavior. The results show that, for any fiber volume ratio, the Type 2 size effect must be expected.

1. Introduction
In the microplane model, the constitutive law of material including the post-peak softening in a representative volume is characterized in terms of vectors rather than tensors. The vectorial form has a powerful advantage. It allows relating the microplane deformations to microcrack opening, frictional slip, fiber pullout and possible breakage. Microplane model M7f for FRC with short discontinuous fibers was developed at Northwestern University [1, 2] and was presented at the 2017 Fibre Concrete conference in Prague. It was shown to fit well the main material tests reported for FRC. In this lecture, the M7f model is used to study two underexplored problems of FRC—the role of fibers in the energetic fracture size effect, and in the penetration of projectiles, or missiles, in FRC walls.

Steel fibers are extensively used in case of structural concrete such as ultra-high performance concrete and new construction technologies [3, 4]. The high tensile strength of steel fibers enhances the tensile behavior of FRC [3, 5, 6]. The steel fibers also enhance ductility and provide good dynamic response to the FRC [6]. The fibers also could capture early age cracking due to shrinkage [7, 8].

There are two causes of size effect, statistical (first properly characterized by Weibull in 1939), and energetic (discovered in 1984 [9, 10]). The latter dominates for reinforced concrete and is the only one studied in this lecture. It is of two types, described by equations:

\[
\sigma_N = \sigma_0 \left(1 + \frac{rD_b}{D}\right)^{1/r} \quad \text{(Type 1 [11])} \\
\sigma_N = B f_t' \left(1 + \frac{D}{D_0}\right)^{-1/2} \quad \text{(Type 2, SEL [9])}
\]

where \(\sigma_N\) is the nominal strength of structure (load divided by characteristic cross section area), and \(\sigma_0, D_b, r, B f_t', D_0\) are constants. The Type II [9, 10, 12] dominates for reinforced concrete and is purely energetic, caused by the stored energy release due to large stable crack growth [13, 14]. The Type 1 occurs for plain (unreinforced concrete), in which the structure becomes unstable as soon as a continuous macro-crack starts growing from a finite damaged microcracking zone, and is caused by
stress redistribution [11, 12]. For very large sizes, Type 1 transits to Weibull statistical size effect [15] (which is omitted from equation (1) and is not discussed here). The Type 2 size effect factor, equation (2), has been adopted for the new revision of the ACI code (Standard 318/2019)—for beam shear, slab punching [16], and compressions struts of strut-and-tie model.

2. Simulation of Scaled FRC Notched Beams

![Figure 1. Specimen Geometry.](image)

The M7 parameters have been calibrated to capture the FRC test reported by Li et al. [6]. Figure 1 shows notched specimens of FRC that have been geometrically scaled to various sizes and simulated by the FE crack band model [17], in which the element size was the same for all specimen sizes. Figure 2 shows the curves of stress versus normalized deflection. The calculated size effect plots of \( \log \sigma_N \) versus \( \log D \) are shown in figure 3 for fiber contents 0, 2%, 3% and 6%, and for four different specimen sizes (or depths) \( D = 400, 800, 1600 \) and 3200 mm.

3. Results for FRC Notched Test

![Figure 2. Three-point bending stress-strain curves.](image)

It is seen that the Bažant SEL (shown by solid curves) fits the data points from FE simulations very well (Figure 3). It is noted that, in these notched fracture specimens, the fibers significantly
elevate the maximum load, which is not the case for the compression tests of standard unnotched test cylinders. It is also interesting that, according to the simulations, the fiber content has no clear effect on the transitional size $D_0$ of the size effect law.

![Size effect plots of FRC in logarithmic scale.](image)

**Figure 3.** Size effect plots of FRC in logarithmic scale.

The measured size effect in notched fracture specimens can be exploited to determine the fracture energy, $G_f$, and the characteristic fracture process zone size, $c_f$, of FRC. To this end, the Type 2 SEL is related to equivalent linear elastic fracture mechanics (LEFM) and is converted to the linear regression plot [10, 12, 15]:

$$Y = AX + C$$  \hspace{1cm} (3)

where $X = D$, $Y = \frac{1}{\sigma_N^2}$  \hspace{1cm} (4)

and $A = \frac{g(\alpha)}{EG_f}$, $C = c_f \frac{g'(\alpha)}{EG_f}$  \hspace{1cm} (5)

Here $g(\alpha)$ = dimensionless energy release function of LEFM and $E$ = Young’s elastic modulus. Figure 4 shows the regression plots of the computed $Y$ versus $X$, for various sizes $D$ and various fiber contents. From these regressions, one gets $G_f = 279, 2424, 2491, 3994$ N/m for fiber contents $0, 2\%$, $3\%$ and $6\%$, respectively. It may be concluded that adding fibers increases the fracture energy of concrete dramatically.

The role of fibers in the Type 1 size effect of FRC has also been simulated. The plain concrete and $2\%$ FRC showed the Type 1 size effect while $3\%$ and $6\%$ FRC did not. The load-displacement curves of unnotched specimens reached a plateau for $3\%$ and $6\%$ FRC and the maximum load became independent of the size. Calculations of projectile penetration into FRC wall as still in progress at the time of writing and will be presented at the conference.
4. Simulation of Projectile Impact into FRC Targets
Another point of considerable interest is the effect of fibers on the resistance to impact. It was previously found at Northwestern [18, 19, 20] that comminution (or fine fragmentation) of material during penetration of projectiles through concrete has a great damping effect, decelerating the projectile, reducing penetration depth and, in the case of full penetration, reducing the exit velocity of the projectile. Most studies concluded that FRC does not significantly reduce the penetration depth or exit velocity after full penetration, but significantly reduces the size of the exit crater and generally limits the size of fragments and the extent of fragmentation [5, 21, 22, 23, 24, 25].

Fig. 5(a) shows the significant improvement of simulation predictions by considering material comminution effect. It is implemented in the microplane model M7 by scaling the stress-strain boundaries based on the local kinetic energy release from comminution. Fig. 5(b) shows the further reduction of projectile exit velocity by increasing the fiber content to 2%. The element deletion criterion has also been adjusted to a larger value for FRC based on the fact that higher fiber content reduces the concrete cracking, leading to a larger strain threshold for the homogenized material. Fig. 6 shows the damage contours of the target (in logarithmic strain) after penetration (with and without fibers). For the case of 2% fiber content, the final crater is seen to become significantly smaller than for plain concrete.

5. FRP Strengthened Flexural Members
External strengthening of RC beams with FRP or textile composites has been shown to be quite effective for diverse structural members such as beams, columns and slabs. The bond quality between the FRP sheets and concrete is generally satisfying. So, the delamination occurs not in the interface but within the concrete immediately adjacent to the interface. The near-interface cracking, which is basically a shear failure, must be expected to lead to a size effect on structural strength. However, the size effect is not considered in the design practice, not in design code and guides for externally bonded FRP systems used for strengthening concrete structures or retrofitting them after damage. This indicates the need for a realistic analysis of the existing test data and their finite element simulations.
Figure 5. a) Effect of material comminution in plain concrete; b) Effect of fiber on projectile exit velocity.

Figure 6. Crater shape after penetration.

FEM analyses, based on concrete damage model model (Microplane Model, M7), consist of the calibration by test data and the subsequent predictions (see Fig. 7a,b). The optimum size effect fits for two different FRP thicknesses are shown in Fig. 7a,b. The shear cracks within the concrete next to bonded FRP sheets propagate along the beam longitudinally, and eventually lead to delamination of the FRP sheet bonded to the RC beam. It should also be noted that the size of the reinforcement affects the cracking patterns. Stiff skin reinforcements results into a distinct size effect even for relatively smaller sizes. As can be seen in Fig. 7b, the predictions for thick FRP sheets indicate a significant size effect. And a sufficiently thin FRP strengthening might change the location of the crack initiation.

6. Conclusions

(i) Compared to concrete without fibers, short fiber reinforcement significantly increases the maximum loads in Type 2 failure of notched fracture specimens and, by implication, also the maximum loads of structures failing only after large stable crack growth (as in shear of RC
(ii) The fiber reinforced concrete showed bigger transitional size in Type 2 size effect; but generally, no clear trend has been observed.

(iii) The values of fracture energy of FRC derived by the size effect method from the computed maximum loads of scaled notched specimens show that introducing fibers into concrete and increasing their content causes the fracture energy to increase dramatically.

(iv) The microplane model M7 with scaled boundaries is shown to be able to capture the effect of material comminution under projectile penetration not only for plain concrete but also for the FRC. The calculations indicate a negligible effect of fiber content on the exit velocity of penetrating projectile but a significant reduction of exit crater size and of the extent of fragmentation.

(v) According to simulations based on calibration by test results, a strong size effect under flexural loading exists in the fracture of concrete-FRP interfaces in RC beams strengthened by FRP. This size effect becomes more prominent for beams strengthened by thick FRP sheets.

Note: Details of the specimen and material properties and of calculations will be given in a separate refereed journal article under preparation.

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