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Discussion on “Assessing the influence of fibers on the flexural behavior of reinforced concrete beams with different longitudinal reinforcement ratios” by Conforti et al. [Structural Concrete, 2020]

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The paper [1] presents useful and valuable information on the flexural behaviour of fibre reinforced concrete (FRC) beams with varying fibre types, fibre dosages and longitudinal reinforcing ratios. The combined effect of fibre and conventional reinforcement in resisting flexure is certainly highly significant and relevant. While agreeing with several of the findings made by the Authors, there are some critical points contained in the paper that we wish to discuss herein.

Experimental results of this [1] and several other studies [2]–[8] clearly indicate that the addition of fibres positively affects cracks spacings, crack widths (before yielding of the conventional reinforcement) as well as member stiffness, and increases the load-bearing capacity of flexural reinforced concrete (RC) elements. After yielding of the conventional reinforcement, however, the addition of fibres may cause crack localisation and consequently compromise the deformation capacity (ductility) of flexural RC members.

As recently outlined by the Discussers [9], the issue of crack localisation in flexural RC members containing fibres has a long standing in the literature; it was analytically and experimentally investigated two decades ago by Pfyl and Marti [2], [3], [5]. The fundamental concept of crack localization due to excessive fibre effectiveness can be explained in a very simple and intuitive manner. Consider a section of a flexural FRC element between two cracks spaced s_{r0} , containing conventional reinforcement as shown in Figure D1a. The tensile component of the flexural response of this element is comprised of contributions by the conventional reinforcement and the fibres. After yielding of the conventional reinforcement, the reinforcing bars exhibit a hardening behaviour, which is characterised by the ratios

f_u/f_y and $\epsilon_{su}/\epsilon_{sy}$ (see Figure D1b). On the other hand, the fibre contribution, for typical dosages adopted in practice, is usually of a softening nature (see Figure D1c). It can be characterised by the fibre softening ratio $f_{1.5}/f_{0.5}$ or f_{R3}/f_{R1} , which may be obtained from direct tensile or bending tests, respectively. Depending on the ratio of fibre contribution to conventional reinforcement contribution (quantified e.g. by $f_{0.5}$ (or f_{R1}) and ρ_s , respectively), the overall behaviour of the member (i.e. the sum of the two contributions) may display a hardening or a softening response. An overall softening response will occur if at any point, the differential loss in force due to the softening behaviour of FRC is greater than the differential force gain attributed to rebar hardening. A softening response is directly associated with deformation localisation in the weakest crack and consequently a reduction of the member deformation capacity prior to rupture of the reinforcing bars. In force-controlled statically determinate systems, this will cause an abrupt and brittle failure. In statically indeterminate systems, a deformation capacity check is required to verify that the force redistribution triggered by the softening response of a part of the structure can actually be provided. For generalised use of FRC in structural engineering, in line with modern codes' design philosophies, it is advisable to strive for members that do not display a softening response before the tensile rupture of the reinforcing bars at ultimate strain ϵ_{su} , but rather provide a reasonably extended strain-hardening range [9]. In addition to the parameters mentioned above, the rebar diameter $\varnothing_s$ is another crucial parameter since it directly influences the crack spacing and crack width, and therefore the softening response of RC members containing fibres. The lower the values of f_u/f_y , ρ_s , $f_{1.5}/f_{0.5}$ (or f_{R3}/f_{R1}), and the higher the values of $\varnothing_s$ and $f_{0.5}$ (or f_{R1}), the greater the risk that the overall response of the member is of a softening nature. A thorough description of the structural behaviour of FRC tension and flexural members containing conventional reinforcement, complemented with mechanically consistent models validated against experimental results obtained by several researchers, is given in [9].

Figure D1: (a) Crack element for FRC flexural members; Tensile behaviour of (a) reinforcing bars and (b) softening FRC [9]

Although the Authors experimentally observed a higher probability of crack localisation as FRC residual strength increases and longitudinal reinforcement ratio decreases, they conclude that for typical ranges of longitudinal reinforcement ratios adopted in practice for RC beams, fibres do not compromise member ductility. We strongly disagree with this last statement for the reasons outlined below.

Firstly, it is important to recognize that reinforcing ratios in flexural elements such as slabs and non-slender beams can readily approach the minimum permissible reinforcement ratio $\rho_{s,min}$ as specified by codes of practice (e.g. *fib* MC 2010, EN1992-1, SIA 262) to achieve economic and sustainability objectives. We therefore object to the Authors' statement that a reinforcing ratio of 0.5% be "very close to the lower bound adopted in practice". Rather, it is commonplace in design practice to adopt reinforcement ratios of less than half of this amount. Furthermore, as stated by the Authors, an increase in flexural bearing capacity due to the presence of the fibres is especially significant at low longitudinal reinforcing ratios. Consequently, if fibres are used in combination with conventional reinforcement, a required bending capacity can be achieved at much lower conventional reinforcement ratios. Hence, designers – aiming at an economical and sustainable dimensioning – would naturally be inclined to further reduce reinforcement ratios, and indeed provide merely the minimum permissible reinforcement ratio $\rho_{s,min}$ (or even less, if resisting the cracking moment is considered sufficient). Indeed, it has been a strategy of certain fibre suppliers to market fibres as a (partial) replacement of conventional

reinforcement. Hence, investigating the ductility of FRC members with reinforcing ratios well below 0.5% is of paramount importance.

As mentioned above, the ductility characteristics of the longitudinal reinforcement decisively affect the ductility (deformation capacity) of RC members. Here, it should be noted that the bending reinforcement used in the experiments carried out by the Authors had very pronounced hardening ratios, with $f_u/f_y = 1.14, 1.23$, and 1.21 for $\rho_s = 0.5\%, 0.9\%$, and 1.2% , respectively. These values are more representative for high ductility Class C steels ($f_u/f_y > 1.15$, which are typically used in seismic design) than for typical Class B steels ($f_u/f_y > 1.08$) used in practice. We note that no values for ϵ_{su} or ϵ_{sy} are reported.

In spite of the relatively high reinforcement ratios ($0.5\% \gg \rho_{s,min}$), high hardening properties ($f_u/f_y > 1.08$) and low rebar diameter ($\varnothing_s = 8$ mm) of the longitudinal reinforcement, Figure 2a of the paper, reproduced here as Figure D2, clearly shows how the beam with $\rho_s = 0.5\%$ tested by the Authors transitions from a hardening (CONTROL) to a softening (S-50) response when fibres were included in the mix, as shown by the fitted dashed lines. It is worth noting that the Authors' Figure 6 clearly indicates that crack c2 localised in Specimen S-50 ($\rho_s = 0.5\%$). The Authors do not comment on the transition between hardening and softening responses, but argue that ductility was not compromised since the deflection at failure, δ_u was not affected by increasing the fibre content (see Table 2 of the paper). However, this observation in a deformation controlled experiment does not give the full picture, and may even be severely misleading: A dramatic difference in deformation capacity would have been observed in a load controlled test setup, where failure had occurred at the peak load, i.e., at a deflection of Specimen S-50 corresponding to merely about 10% of that observed in the control specimen. The deformation capacity beyond the peak load observed in the experiments could only be activated in a hyperstatic structure, and provided that other parts of the structure were able to resist the higher loads caused by the softening response of the member. The "compression zone failure" reported by the Authors, observed after substantial softening in Specimen S-50, and the corresponding rotation capacity, are relevant merely in this context, i.e., when checking rotation demand vs. capacity.

Figure D2: Reproduction of Figure 2 in [1] highlighting the transition between a hardening response (see specimen “CONTROL”) and a softening response (see specimen “S-50”) at the onset of yielding of the longitudinal reinforcement.

In conclusion, while the Authors present very interesting and valuable findings, we strongly disagree with their conclusion that the ductility of fibre-reinforced reinforced concrete is not an issue for “practical reinforcement ratios”. It may be negligible for high reinforcement ratios and in members containing reinforcement with high strain hardening properties. However, it severely affects the ductility of RC elements with low reinforcement ratios of normal reinforcement (Class B) containing fibres as shown by several experimental campaigns [2], [3], [5], [10]–[15]. The reader is referred to [9] where performance charts capable of predicting the critical fibre residual tensile stress for an SFRC section with a given flexural conventional reinforcement ratio, reinforcing bar diameter and fibre softening ratio are presented.

Notation

$f_{0.5}$ = residual axial tensile stress offered by fibres at a Crack Opening Displacement COD = 0.5 mm

$f_{1.5}$ = residual axial tensile stress offered by fibres at a COD = 1.5 mm

f_{R1} = residual flexural tensile stress offered by fibres at a Crack Mouth Opening Displacement CMOD₁

f_{R3} = residual flexural tensile stress offered by fibres at CMOD₃

f_u = ultimate strength of reinforcing bar

f_y = yield strength of reinforcing bar

s_{r0} = crack spacing

$\emptyset_s$ = diameter of reinforcing bar

ϵ_{su} = ultimate strain of reinforcing bar

129 ϵ_{sy} = yield strain of reinforcing bar

130 ρ_s = longitudinal conventional steel reinforcement ratio

131 $\rho_{s,min}$ = minimum reinforcement ratio of conventional steel

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