COMPATIBLE DESIGN OF FC AND RFC STRUCTURES WITH STANDARD DESIGN OF PLAIN CONCRETE AND RC STRUCTURES

Jiří Krátký [1], Jitka Vašková [2]

Abstract

Some aspects of design considering uncracked and cracked behaviour of Fibre Concrete (FC) are discussed. ULS of the first macro-cracking is the limit of quasi-linear and quasi-plastic behaviour and design of FC. The ultimate strains of FC in post-cracking stage, residual equivalent tensile strengths and also ultimate crack widths and deflections of FC and Reinforced FC (RFC) structural members are preferably discussed at ULS and SLS. The design of FC in both load bearing capacity and serviceability using appropriate material properties should be compatible with standard design of structural members of plain, reinforced and prestressed concrete, e.g. [1]

Keywords: Fibre concrete (FC), reinforced fibre concrete (FRC), plain concrete (PC), reinforced concrete (RC), material properties, strength, structural design

.

1 Introduction

Concrete structures are designed using the ultimate states concept (ULS, SLS); these should be valid for FC and FRC structures as well as considering different characteristics of FC.

FC (with sufficient fibre volume ratio $\rho_{V,f}$) has usually in compression greater values of ultimate strains than plain concrete, greater value of tensile strength at cracking and quite different post-cracking behaviour in tension as an effect responsible for larger ductility of FC and RFC structures. These all are the main aspects which should be taken into account in design. For determination of load-carrying resistance in design, designers must be provided with corresponding parameters of strength and strains.

All these parameters should also help to classify uniquely FC of a structure and express its specific behaviour both in formation of a tensile crack and residual or equivalent strength and agreed values of ultimate strain, and the same allowable crack width and working loads.

Therefore the strength class of FRC should have more detailed denomination.

.

---

1) CTU in Prague - Faculty of Civil Engineering, Department of Concrete and Masonry Structures, Thákurova 7, 166 29 Prague 6 Czech Republic, e-mail: K133@.fsv.cvut.cz

2) CTU in Prague - Faculty of Civil Engineering, Department of Concrete and Masonry Structures, Thákurova 7, 166 29 Prague 6 Czech Republic, e-mail: jitka.vaskova@.fsv.cvut.cz

2 Material properties of FC

Representation of the characteristic stress-strain relation of FRC is very important for structural analysis, schematic diagram of this characteristic relationship may be simplified for the structural design of cross-sections according to Fig.1. The characteristic diagram shall be specified by characteristic strengths of FC (compressive strength f_{fck}, cracking tensile strength f_{fctk}, residual tensile strength $f_{fctk,res}$ and / or equivalent tensile strength $f_{fctk,eq}$) guaranteed by initial tests of standard specimens, and by characteristics strains of FRC (ultimate compressive strain ε_{fcu} , compressive strain at the quasi-elastic behaviour limit $\varepsilon_{fc,el}$, cracking tensile strain $\varepsilon_{fct,cr}$ and ultimate tensile strain $\varepsilon_{fct,u}$) defined usually by a deterministic method.

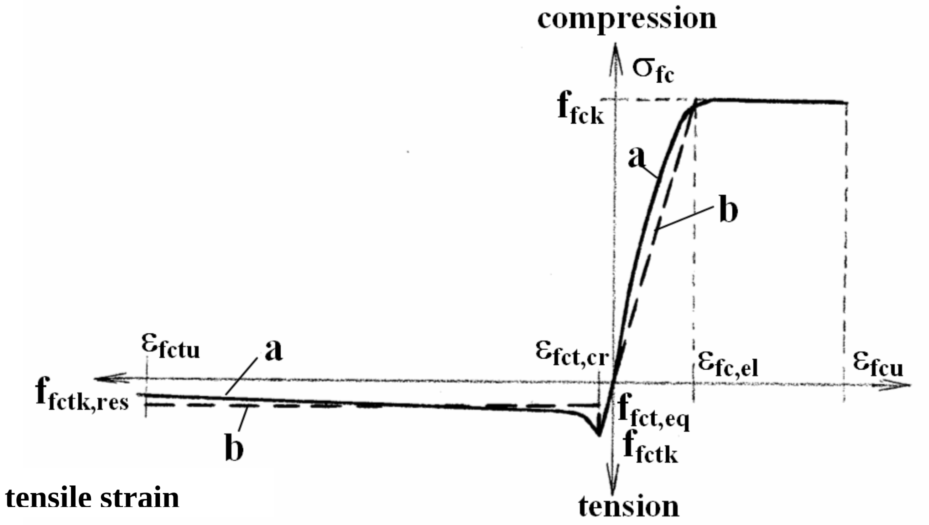

Fig.1 Representation of the characteristic stress-strain relation (a) and its simplification (b)

Especially for the cracking tensile strength of FC it is not proper to derive its value indirectly from the compressive strength of FC using very approximate empirical relations for plain concrete as this strength can be much higher than in concrete without fibres, depending on the amount and type of fibres added [2]. The main difference between FC and PC is the tensile ductility evident from the post-cracking residual strength and the ultimate tensile strain. Characteristic values of FRC strengths can be used also for more stringent classification of FRC, e.g. [3]

$$\text{FC:}\quad f_{fck}\,/\,f_{fck,cube}\ -\ f_{fctk}\,/\,f_{fctk,eq}\ -f_{fctk,sp}, \qquad (1)$$

where $f_{fctk,sp}$ is the characteristic splitting tensile strength for production control of FC.

When the strains ε_{fc} of the FC cross-section are between $\varepsilon_{fct,cr}$ and $\varepsilon_{fc,el}$ the behaviour of the section can be considered as quasi-linear elastic and for stress distribution the theory of elasticity can be used. In this case no tensile cracks occur in the section. After cracking of FC the stress distribution in the cross-section rapidly changes with the strains which shall rest between $\varepsilon_{fct,u}$ and $\varepsilon_{fc,u}$. Then the behaviour of the cross-section is quasi-plastic, ensuring the ductility.

Fig.2 shows results of experimental tests of preferable beam specimens 150/150/700mm with load controlled by deflection. The difference in resistant force F_R at ULS of macro-cracking and post-cracking stage of PC and FHRC is evident from Fig.2, the difference in toughness is large.

The graphs show the difference in the first crack load, the post cracking behaviour and toughness between PC and FC with steel fibres (fibre volume ratio $\rho_{V,f} = 1\%$).

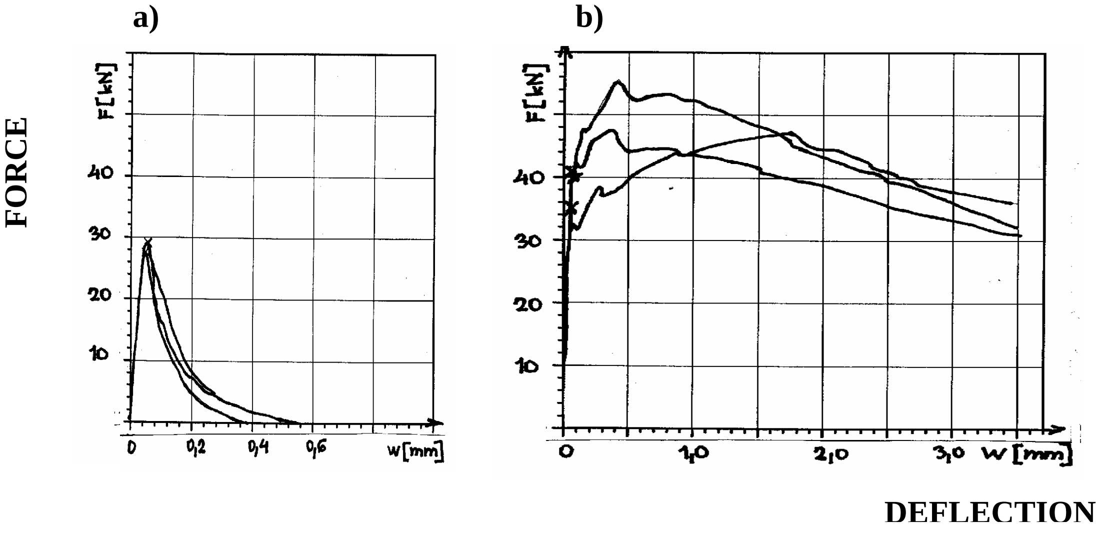

Fig.2 Force – Deflection diagram for preferable test specimens
a) PC b) Fibre highly reinforced concrete (FHRC) with Dramix fibre $\rho_{V,f} = 1\%$

3 The ultimate limit states (ULS) of FC

For ULS design the characteristic relation σ_k - ε_k (Fig. 1) shall be substituted for the design relation σ_d - ε_d. The modification of the characteristic relation σ_k - ε_k is done by using design values of FC strength f_{fcd} and f_{fctd} for the same characteristic strains.

The values of the design compressive and tensile strength f_{fcd} and f_{fctd} may be defined separately with the relation to the fibre volume ratio $\rho_{V,f}$. under quasi-elastic behaviour of uncracked FC:

$$f_{fcd} = \alpha_{fcc,pl} \cdot f_{fck} / \gamma_{fc,c} \tag{2a}$$

$$f_{fctd} = \alpha_{fcc,pl} \cdot \kappa_h \,.\, f_{fct,k} / \gamma_{fc,t} \tag{2b}$$

where $\alpha_{fcc,pl}$ ($\alpha_{fcc,pl}$) is the coefficient taking account of better ductile properties of FRC at compressive (tensile) strength, in the first crack performance with change fibre volume fraction ρ_{Vf} (ULS of macro-cracking) in comparison of PC,

κ_h the tensile strength correction, $\kappa_h = 1{,}6 - h\ [\mathrm{m}] \geq 1{,}0$ (3)

$\gamma_{fc,c}$ ($\gamma_{fc,t}$) the partial safety factor for FRC in compression (tension) of FRC, (values of safety factors depend on amount of fibres in mixture)

For FC with steel fibres the following expressions may be used:

$$\alpha_{fcc,pl} = \alpha_{fct,pl} = 0{,}8 + 0{,}25\ .\ (\rho_{vf} - \rho_{vf,min}) \leq 1{,}0 \tag{4}$$

$$\gamma_{fc,c} = 1{,}5 - 0{,}25\ .\ (\rho_{vf} - \rho_{vf,min}) \geq 1{,}3 \tag{5}$$

$$\gamma_{fc,t} = 1{,}5 - 0{,}25\ .\ (\rho_{vf} - \rho_{vf,min}) \geq 1{,}2 \tag{6}$$

where $\rho_{V,f}$ is fibre volume ratio in %, $\rho_{V,f} = V_f / V_{fc} \geq \rho_{V,f,min}$ (7)
V_f , V_{fc} volume of fibres, volume of FC,
$\rho_{vf,min} = 0{,}5\%$.

For FRC the ULS of the cross-section can be attained either by the quasi-elastic behaviour of an uncracked section or by the quasi-plastic behaviour of usually cracked cross-section. For members subjected to bending, or to bending with axial force, (see Fig. 3), structural analysis may based on the quasi-linear elastic theory or non-linear plastic theory as well as on simplify quasi-plastic theory.. The greater section resistance of both behaviour types for the applied internal forces M and N is decisive. For bending with tensile force or small compressive force the quasi-elastic behaviour can usually be in compliance with the criterions according to Figure 3a. For the quasi-plastic behaviour of the cross-section the strains and stresses shall be in compliance with the criterions according to Figure 3b.

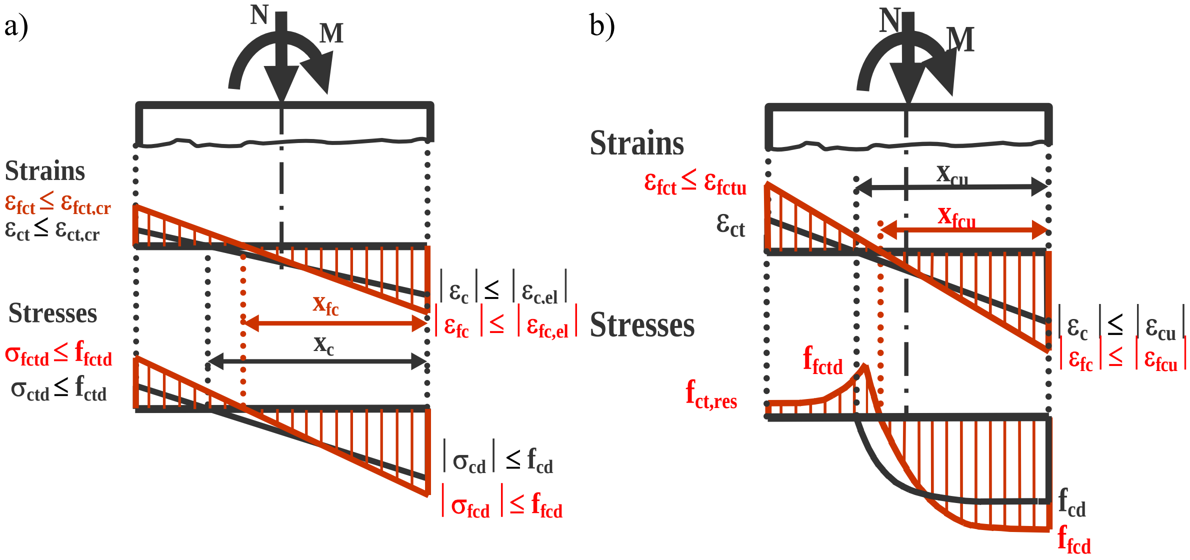

Fig.3 Strains and stresses of SFRC section and a comparison with PC section
a) quasi-elastic behaviour of uncracked sections
b) quasi-plastic behaviour of cracked sections

The interaction diagrams of design resistant forces M_{Rd} and N_{Rd} for quasi-elastic (A) and quasi-plastic (B) behaviour of FC and PC cross-sections are shown in Figure 4. When in the FC cross-section there are also reinforcing steel bars their design resistance can be superimposed to the resistant forces of the usually cracked FRC section as given in Fig. 5.

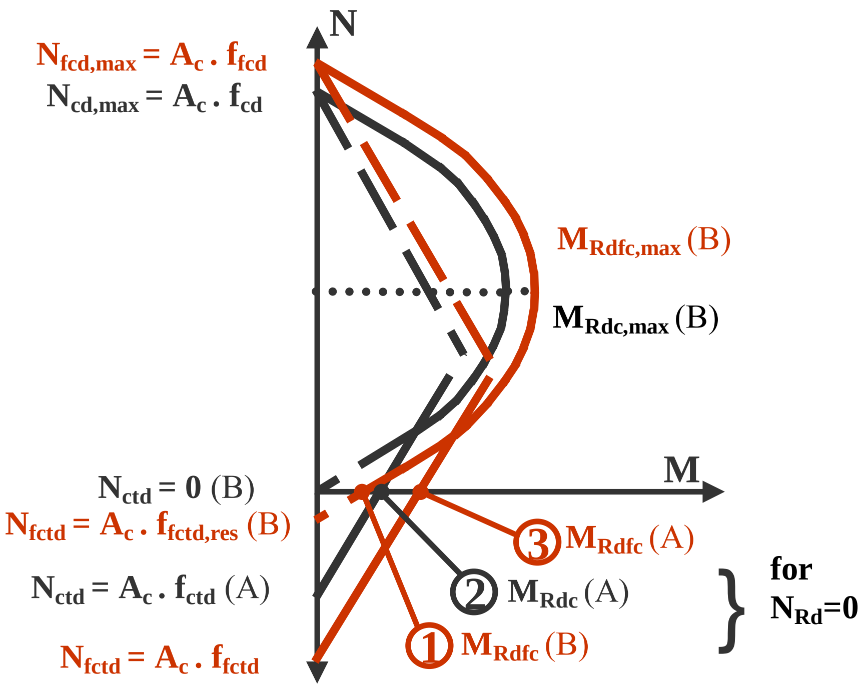

Fig.4 The interaction diagrams of M_{Rd} and N_{Rd}

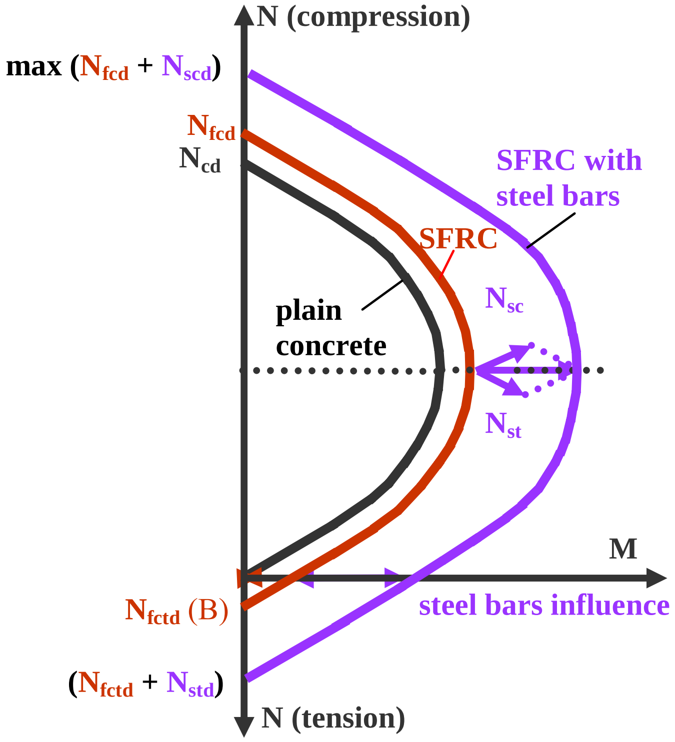

Fig.5 Influence of reinforcing steel bars to the resistant forces of the FC section

4 THE SERVICEABILITY LIMIT STATES (SLS) OF FC

Reliability of FC members under SLS can be ensured by two methods. The safest method is to avoid cracking under service loads (for PC and/or lightly reinforced concrete structures [1]), i.e. to use the characteristic stress-strain diagram with limit strains $\varepsilon_{\mathrm{fct,cr}}$ and $\varepsilon_{\mathrm{fc,el}}$ (Fig.1) and characteristic values of loads at linear elastic behaviour of the FC member. This is not necessary where the quasi-linear elastic analysis has been used under ULS of FC. The more complicated method is to accept cracking in FC members without reinforcing steel bars under service loading but that can occur frequently or last for a long time. For such loading the characteristic residual strengths of FC shall be smaller than the characteristic post-crack strengths in Fig.1 represented currently by short time tests [2].

After cracking of FC members the cracks widths increase so that durability of FC and/or load bearing capacity of the FC member decreases. The use of steel reinforcing bars is rather necessary in such a case for the RFC member to control the crack width and length. The crack control by limitation on tensile strains after cracking is uncertainty for working life of FC structures.

5 Conclusions

For efficient performance of FC structures it is necessary to classify the characteristic values of material strength and strains. For the defining of FC structures resistance under ULS shall be used either the quasi-elastic behaviour of an un-cracked section or the quasi-plastic behaviour of a usually cracked section resulting from the applied internal forces M and N.

For beams made of FC without any reinforcement, occurrence of crack in the SLS should be avoided. If crack are permissible, it is recommended to use steel reinforcing bars.

Acknowledgements

This outcome has been achieved with the financial support of the Grant Agency of the Czech Republic Grant Project No. 103/07/1275 In this undertaking, the results gained in the projects GACR No. 103/06/0685 and No. 103/06/1559 were exploited.

References

[1] EN 1992-1-1:2004: Eurocode 2: Design of concrete structures – Part 1.1: General rules for buildings. CEN 2004, 225 pp

[2] Vašková, J., Vodička J. Testing of FRC tensile strengths, in Proceedings of Conference 10th Concrete Days 2003, Czech Concrete Society, Prague 2003, (Czech language), pp. 310-315.