Chapter 9
Fibres in Concrete Structures

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Abstract Fibres in concrete opened new ways of thinking in design and application of concrete as a structural material. Short fibres provide efficient ways to improve some specific properties of concrete members such as ductility, deformability, durability, as well as load bearing capacity. Parallelly bonded long fibres may form FRP reinforcements that can be applied internally like conventional prestressed or non-prestressed reinforcements. Otherwise they can be applied as externally bonded (EBR) or near surface mounted (NSM) reinforcements. Many applications show successful use. The present chapter intends to give an overview of the principal aspects of fibre-reinforced concrete, and on the other hand the main characteristics of EBR or NSM strengthening methods by using FRP. Specific details are given both on material and design aspects.

9.1 Introduction

Fibres have become important for concrete structures. A large variety of fibre applications in various members and for various purposes using different fibres is known from the last decades. These engineering applications often followed early empirical applications but are extended for further optimization of material properties.

Fibres are very thin compared to the dimensions of concrete elements, but still they may provide considerable improvements of material properties if used in reasonable ways. Fibres can be used either in their long form or cut into pieces and mixed into the concrete. These are often the same fibres. Bonded fibres can be

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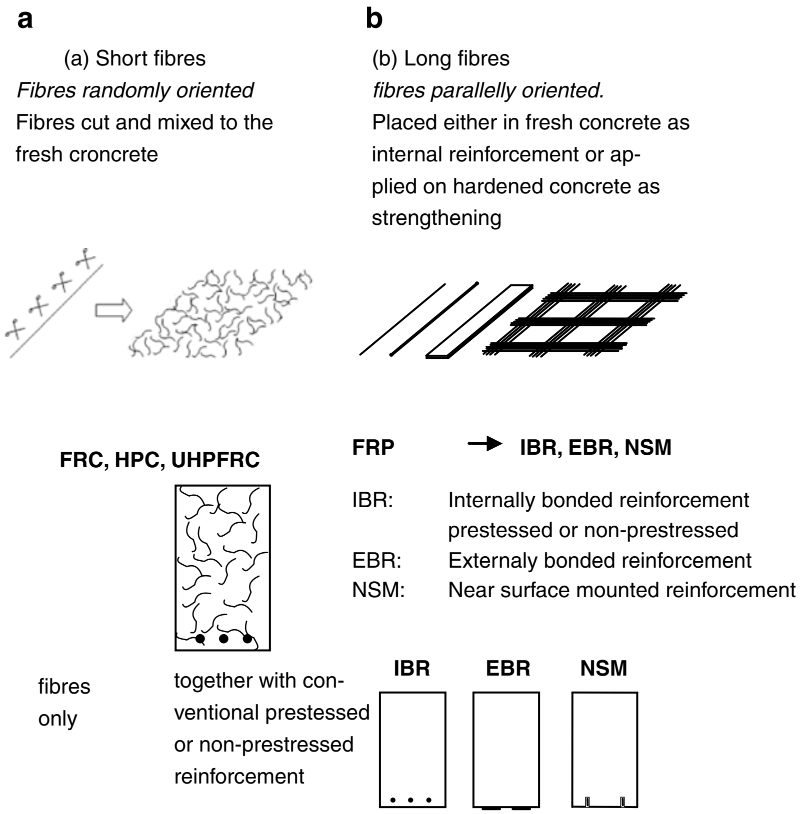

Fig. 9.1 Principles of using fibres for concrete structures: (**a**) short fibres (randomly oriented), and (**b**) long fibres (oriented)

formed similar to reinforcements like conventional prestressed or non-prestressed reinforcements.

Two different principles of using fibres for concrete structures are presented in Fig. 9.1. Fibres originally appear in long from, i.e. their length to diameter ratio is high.

The most traditional way of using fibres is when the fibres are cut or broken into short pieces and are mixed in a matrix where good bond between the fibres and the matrix is possible (Fig. 9.1a).

An adobe brick is shown in Fig. 9.2a as an example that natural fibres are able to keep the clay together even after cracking (if water is excluded).

This idea of fibre applications has been also adopted for concrete structures with or without simultaneous application of conventional prestressed or non-prestressed reinforcement.

The other way of using fibres (Fig. 9.1b) is to keep them in their long from (as far as they fit into the element) and place them accordingly to follow the high tensile stresses. A traditional application of this idea is shown in Fig. 9.2b, where

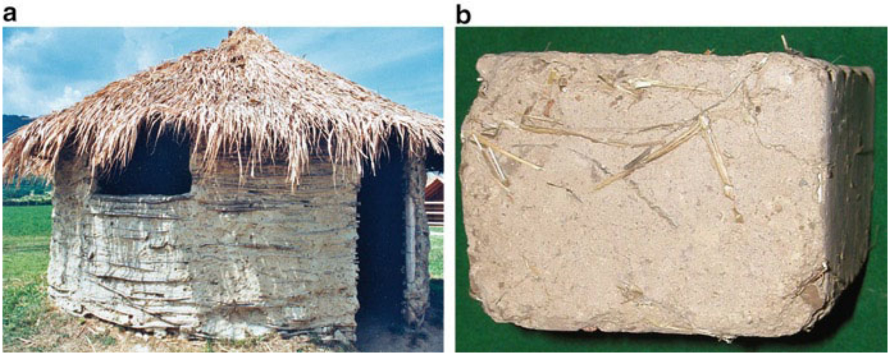

Fig. 9.2 Traditional applications of fibres: (**a**) Adobe brick, and (**b**) rural house: clay wall with wooden reinforcement

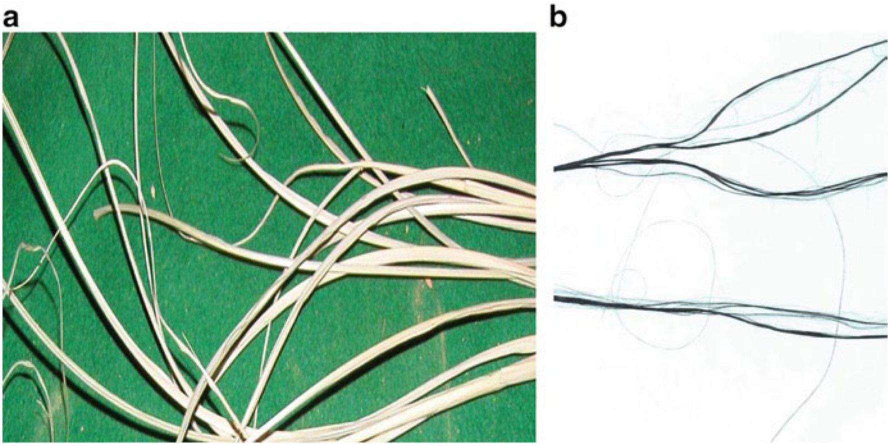

Fig. 9.3 Natural and artificial fibres: (**a**) long grass, and (**b**) carbon fibres

long pieces of tree branches are applied circumferentially in a simple clay wall in order to provide continuity against cracks and confinement for the whole wall. The reinforcement follows the circular tensile forces and is easy to apply during the production of the wall. This way of application may be considered as the origin of embedded reinforcement or of additional strengthening. The idea is still put into practice today by forming FRP (fibre reinforced polymer) reinforcements made of many fibres that are parallelly bonded together. It is then possible to apply them as internally bonded reinforcement (IBR) or externally bonded reinforcement (EBR) for strengthening or near surface mounted (NSM) reinforcements also for strengthening purposes (Fig. 9.1b).

Figure 9.3 shows the similarities between natural (long grass) fibres and artificial (CFRP) fibres.

9.2 Short Fibres in Concrete

The simplest fibre application is to mix short fibres (metallic or non-metallic) into conventional concrete. This concrete is then called fibre-reinforced concrete (FRC). Fibres (especially steel fibres) improve ductility and deformability as well as serviceability and durability.

A more advanced way of application is obtained by reducing both the maximum aggregate size and the length of the fibres. It generally leads to a mix that is often called ultra high performance reinforced concrete (UHPFRC), owing to the considerable improvement in material properties (especially in tensile strength) if a high amount of fibres is used.

Application of steel fibres in plain concrete improves material properties such as toughness, ductility, fatigue, and impact resistance (Naaman 1992; Balaguru and Shah 1992; Reinhard and Naaman 1999). For this reason, fibre concrete is especially applied for concreting industrial floors, roads and pavements, airfield runways, bridge decks, tunnels, and other concrete and reinforced concrete structures. Fibre reinforcement can be effectively used as retrofitting material as well. However, as previous tests indicated, steel fibre reinforcement is not effective at improving the moment capacity of reinforced concrete members. However, fibres may have a significant effect on the shear resistance of reinforced concrete beams and slabs (Falkner et al. 1994) (punching shear). Fibres may reduce the amount of stirrups and the congestion of the reinforcement in high shear regions. Fibres do not only increase shear capacity but also provide substantial post-peak resistance and ductility (Kovács and Balázs 2003). Moreover, by using steel fibres in plain concrete, a substantial decrease of the crack width can be achieved.

9.2.1 Performance of Fibre-Reinforced Concrete

Figure 9.4 intends to give a summary in a special way of the influences of steel fibres in concrete for various contents of steel fibres. The abscissa is the fibre content starting from zero and reaching the level of fibre contents for UHPFRC. The ordinate indicates the performance of concrete in all possible ways that can be positively influenced by fibres. The heading of the figure presents the words CONCRETE, FRC and UHPFRC parallel to abscissa. Concrete is the reference with no fibres. FRC means typically 20 kg/m³ (0.25 vol.%) up to about 80 kg/m³ (1 vol.%) fibre contents, UHPFRC normally indicates higher fibre dosages that are still possible to produce in conventional concrete mixers.

Regarding the improvement in performance of concrete as the steel fibre content increases, low amounts of fibres already produce an increase of toughness that is also mentioned as increase in the energy absorption of concrete. Fibres help to transform tensile forces through the initially small cracks, something that is often called cracks bridging mechanism. These include improved deformation capacity, especially the increase in the failure strain of concrete in compression. Fatigue and impact resistance can be also improved. At this phase, the existence of residual

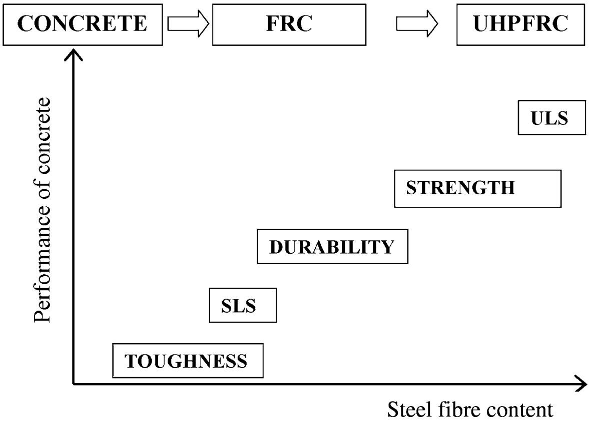

Fig. 9.4 Improved performance of concretes by increasing the content of steel fibres (schematic diagram)

tensile strength of fibre concrete after the appearance of cracks is very important. All these may lead to an improved behaviour both in terms of serviceability and of durability. The higher is the fibre content the greater the improvement.

A higher fibre dosage may produce even more considerable improvements. The strain softening behaviour (FRC) may change to strain hardening behavior (UHPFRC), thus improving also the ultimate (ULS) behaviour. At this level of fibre dosage, improvement in tensile as well as in compressive strength is possible (Naaman and Reinhardt 1995).

Residual tensile strength after cracking is one of the most important design parameters for FRC members. A typical flexural test is shown in Fig. 9.5, which conforms to the conditions set out by DAfStb (2010). The specimen has a section of 150 × 150 mm and a length of 700 mm with a span of 600 mm (Fig. 9.5a). Specimens were loaded in 4-point bending in deflection control. Figure 9.5b, c present two cases where the number of steel fibres in the failed cross-sections were considerably different (22 or 40 fibres) even if the same mix was used (the specimens were cast on the construction site by the construction company). Figure 9.5d indicates that the number of fibres in the failed section has a very important influence on the level of residual tensile capacity. By presenting all of the test results (Fig. 9.5d), an almost linear tendency is observed between the number of steel fibres in the failed cross-section and the so-called equivalent residual flexural tensile strength.

9.2.2 Tests with Steel Fibre-Reinforced Prestressed Concrete Beams

Three prestressed pretensioned concrete beams of 80 × 120 mm cross-section and 2 m length were prestressed by a simple seven-wire strand (∅12.9 mm, $f_{ptk} = 1{,}770$ N/mm², $f_{p,0.1} = 1{,}550$ N/mm², $A_p = 100$ mm²) at the core point of the section (Fig. 9.6). Specimens were prestressed simultaneously along a single strand, and did not contain any other non-prestressed reinforcement (not even stirrups) except the prestressing strand. The prestressing force was released gradually by hydraulic jacks. DRAMIX ZC 30/.5 hooked-end fibres were applied in 0 V%, 0.5 V% and 1.0 V% fibre contents.

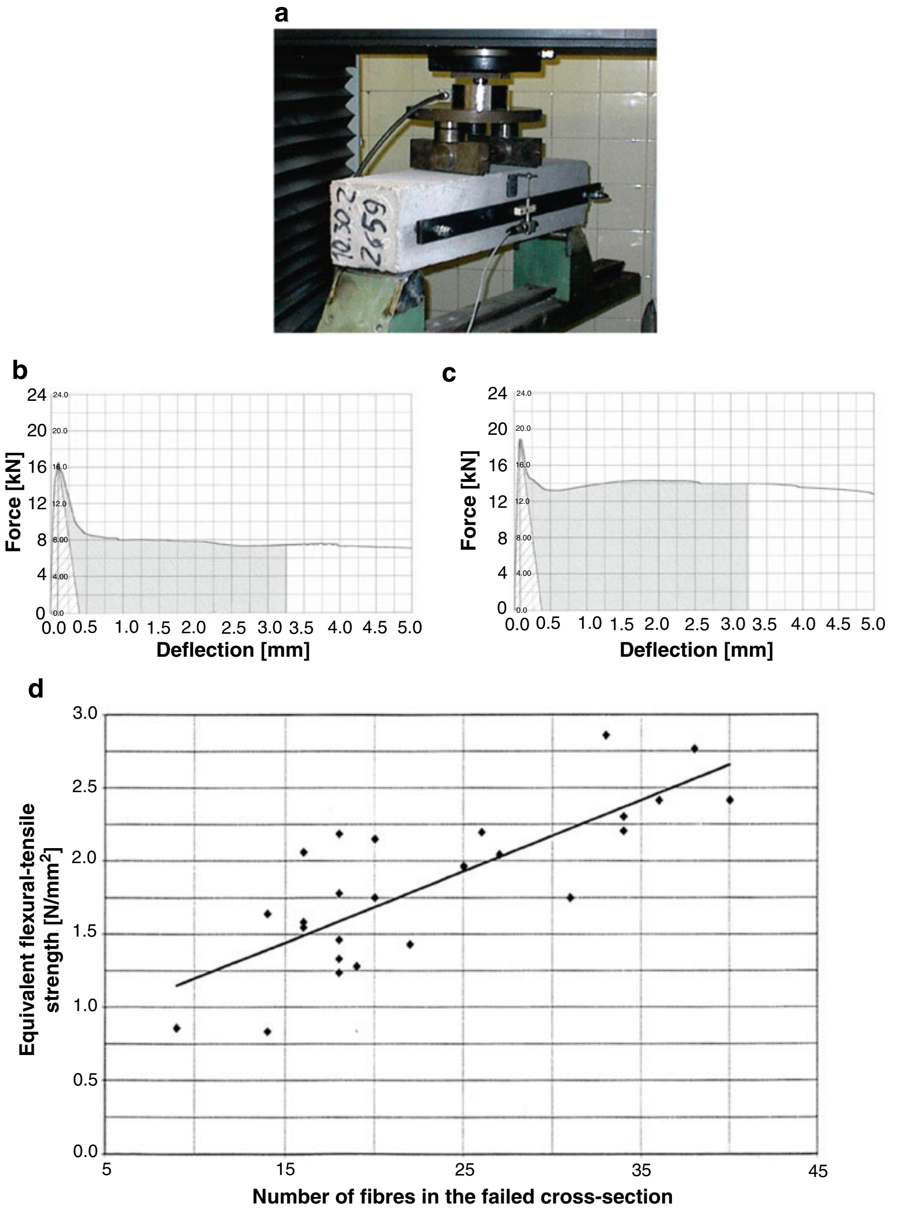

Fig. 9.5 Flexural tests on steel fibre-reinforced beams in deflection control: (**a**) test setup, (**b**) load-deflection curve for 22 fibres in the failed section, (**c**) load-deflection curve for 40 fibres in failed section, and (**d**) equivalent flexural tensile strength vs. number of fibres in the failed section

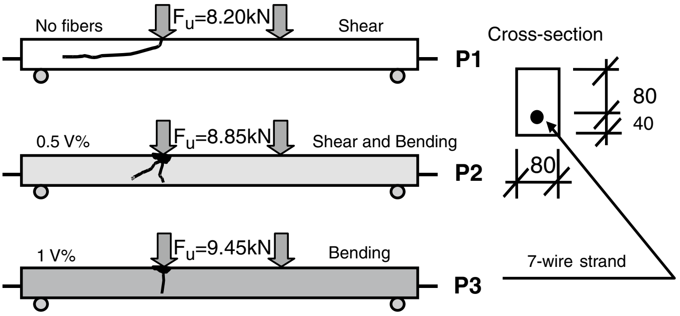

Fig. 9.6 Failure modes of prestressed pretensioned fibre-reinforced concrete beams (fibre reinforcement: Dramix ZC 30/.5)

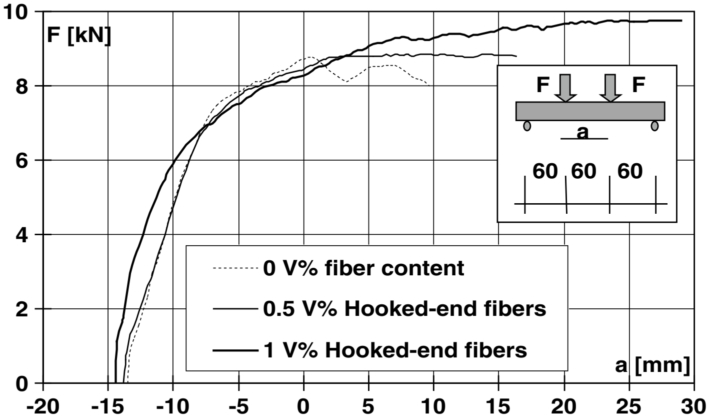

Fig. 9.7 Load versus mid-span deflection in four point bending of prestressed concrete beams

Four-point bending tests were carried out on the prestressed pretensioned concrete beams (Figs. 9.6 and 9.7). Failure loads and failure modes are presented in Fig. 9.6. Results indicate that the fibre content influences the failure load and even the failure mode. By increasing the fibre content the failure load increases and the failure mode may change from one due to shear (*top*) to a combined one in shear and bending (*middle*) and further to a clearly flexural failure mode (*bottom*). Failure of the beam without fibre reinforcement was very brittle and explosive.

9.3 Long Fibres in Concrete

If long parallel fibres are embedded into a resin matrix, they can be formed into reinforcement (FRP reinforcement) that looks similar to conventional prestressed or non-prestressed steel reinforcement. Alternatively, they may be formed as a mesh.

The advantages are especially their high strength, high fatigue strength and electrolytic insensitivity. However, their sensitivity against lateral forces needs special care during application. These FRP reinforcements can be placed into concrete before casting as internally bonded reinforcement; on the other hand they can be externally bonded on the surface of the concrete member (EBR) or into grooves that are cut in the concrete cover (NSM) as was shown in Fig. 9.1b. With internal application a new member is produced; external application is common in strengthening.

Concrete structures may need strengthening due to the deterioration of material properties (including excessive cracking or deflection), the increase in loads or the modification of the strengthening system. Strengthening should fulfill the following requirements:

- easy applicability even by keeping the live load (at least partly)
- short period of time required for strengthening work
- considerable increase in service life with limited maintenance after strengthening
- aesthetic solution not disturbing the appearance of the structure
- economic solution, at least in relative terms.

In general, we can choose from the following strengthening materials and techniques:

- supporting construction
- concrete overlay
- shotcrete layer
- SCC layer
- external prestressing
- steel jacketing
- steel plate bonding
- externally bonded FRP
- near surface mounted reinforcement.

The present contribution discusses the last two cases.

External bonded strengthening with FRP goes back to the end of ‘80s (*fib* 2001). The near surface mounting type of strengthening was first published by Asplund (1949) but became widely known after the research by Blaschko (2001). A generic description of NSM strengthening is presented by Szabó and Balázs (2008).

9.3.1 Design Principles

The design principles of CFRP strengthening are:

- the design of strengthening should be based on the stresses and deformations of the structure before strengthening (Fig. 9.8),
- strengthening elements are stressed only from loads applied after the strengthening procedure,

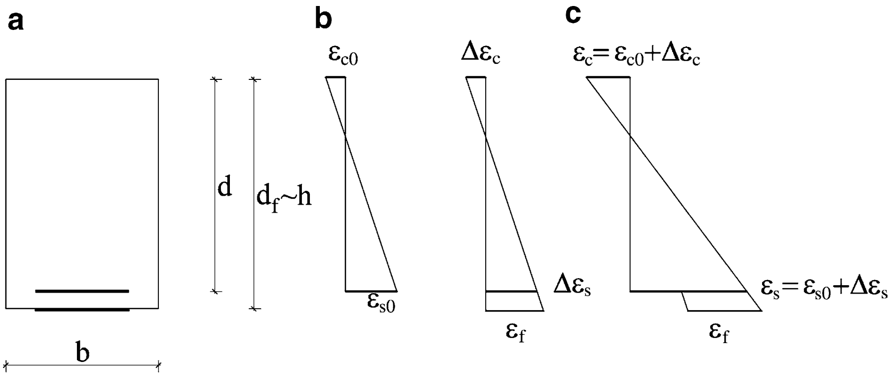

Fig. 9.8 Strain profiles before and after strengthening: (**a**) strains before strengthening, (**b**) strains from loads above strengthening, and (**c**) strains of strengthened member

- the design of strengthening should include the analysis of all possible failure mechanisms,
- flexural strengthening is not always enough; shear strengthening may also be required.

Possible failure modes of the strengthened members are given in various publications, e.g. *fib* (2001) and *fib* (2006), including initiation of failure by any constituent. All possible failure modes should be analysed during design. Special attention should be given to the debonding failure modes (Hollaway and Leeming 1999).

The safety concept for design is that the governing failure mode should be relatively ductile, i.e. steel yielding or concrete crushing prior to rupture or debonding of the FRP strengthening material.

9.3.2 Case Study

A typical example is shown in Fig. 9.9. The reinforced concrete grain silo lost its capacity to resist the circumferential tensile forces that was originally provided by prestressing strands (Balázs and Almakt 2000). The bottom part of the silo was constructed of 12 prefabricated concrete pieces. The most reasonable way of strengthening was to apply CFRP strips that are insensitive to electrolytic corrosion. The application step in Fig. 9.9 indicates the closing of strengthening strips by overlapping. The design included analysis of forces and deformations. The final design criterion was not the maximum tensile force but the maximum allowable opening between the prefabricated concrete pieces.

Fig. 9.9 Strengthening of a grain silo with CFRP strips

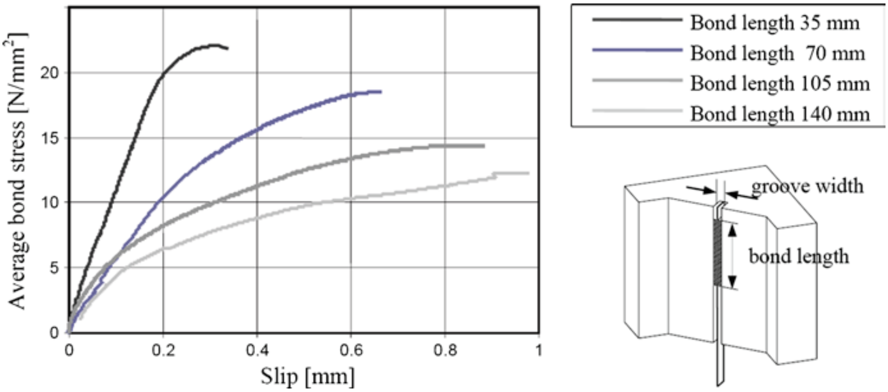

Fig. 9.10 Characteristic average bond stress-slip curves for various bond lengths

9.3.3 *Bond along NSM Reinforcement*

For proper study of the force transfer of the near surface strengthening, an L shaped pull-out specimen was developed (Szabó and Balázs 2008). The specimen (Fig. 9.10) was designed to reduce eccentricities during loading. The special form of the concrete specimen enabled proper view of the likely failure surface. It also provided the possibility of measuring the displacement of both loaded and unloaded ends of the bond length. In the case of FRP strips, the bond on lateral surfaces is considerably influenced by the lateral confinement of the specimen induced also by frictional stresses developed at supporting planes. Therefore, the bond length was shifted as much as possible to the top of the specimen. In addition, the bond length was kept

Table 9.1 Long-term properties of strengthenings

Mechanical properties	Environmental	Hazards
Relaxation	Alkalis	Impact
Fatigue	Water	Fire
	Chloride ions	Vandalism
	Freeze-thaw	
	UV radiation	

to a certain distance from the bottom edge of the specimen. Over that distance the strip was kept free to avoid fastening type of failure.

Typical average bond stress vs. slip diagrams are shown in Fig. 9.10. Slip at the loaded end was examined in the case of four bond lengths. At small bond lengths, the steep ascending branch of the average bond stress vs. the slip curve was recorded in the first stage of loading. Approaching the failure load the tangent of the curve decreased showing gradual failure of the connection. The inclination of the curve decreased when increasing the bond length, thus showing an average bond stress decrease and an increase in the deformation capacity of the connection. The characteristic failure was a shearing failure of the adhesive near the FRP surface. The residual stress was the result of friction between the sheared adhesive surfaces. The diagram also shows that the average bond strength deceases by increasing the bond length, thus indicating the non-uniform distribution of bond stresses along the bond length. The existence of an effective bond length, i.e. a bond length beyond which increasing the length does not result in a considerable increase of the anchorage capacity of the FRP strip, is noticeable.

9.3.4 Future Work on Long-Term Properties of FRP Strengthenings

Long-term material properties of FRPs (relaxation, fatigue) are considered favourable especially for carbon fibres embedded into epoxy resin. Environmental influences should be also considered for specific cases. Special consideration may be required if impact, fire or vandalism cannot be excluded (Table 9.1).

9.4 Conclusions

Fibres have become important for concrete structures. The engineering applications often followed early empirical applications, but are extended for further optimization of material properties. Fibres can be used either in their long form or cut into pieces and mixed into the concrete. These are often the same fibres. Bonded fibres can be formed similarly to reinforcement, like conventional prestressed or non-prestressed reinforcement.

The most traditional way of using fibres is when the fibres are cut into short pieces and are mixed in a matrix. This idea of fibre application has been also adopted for concrete structures with or without simultaneous application of conventional prestressed or non-prestressed reinforcement. Short fibres provide efficient ways to improve some specific properties of concrete members such as ductility, deformability, durability as well as load bearing capacity.

Parallelly-bonded high-strength non-corrosive fibres may form FRP reinforcements that can be applied internally like conventional prestressed or non-prestressed reinforcements. Otherwise they can be applied as externally bonded (EBR) on the surface of the element or near surface mounted (NSM) reinforcements bonded into pre-cut grooves.

The present chapter gives specific details on how the performance of the elements may increase in the case of fibre-reinforced concretes. Test results are shown for the improvement of failure load and failure mode of prestressed pretensioned concrete elements by applying steel fibres.

Design aspects and general considerations are given for EBR as well as for NSM strengthening with FRP including test results on the bond capacity of NSM reinforcements.

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