Crack arrest by internal compressive stress field induced by external tensile loading

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In brittle materials such as concrete and ceramics, fibre reinforcement has been widely accepted as an effective way to improve their toughness and strength. Significant increases in toughness, 2 to 3 order or magnitudes higher than that of the plain matrix, have been achieved [1–3]. Such large improvements are generally associated with fibre debonding, fibre plastic deformation, and fibre pull-out. On the other hand, strength enhancement is much less impressive when low to moderate fibre contents are used. A marginal effect of fibres on increased strength is by impeding crack propagation [4, 5]. For continuous aligned fibre composites, Aveston *et al*. [6] have derived an explicit equation relating composite first cracking strength (σ_{mu}, at which a matrix crack propagates throughout a cross-section) to fibre, matrix and interface properties. They found that σ_{mu} is weakly dependent on fibre modulus to a 1/3 power, and on fibre volume fraction to a 2/3 power. Hence, strength enhancement is expected to be moderate unless very high fibre content is employed. For practical applications, however, high cost and processing difficulties associated with high fibre contents might hinder a widespread use of fibre reinforced composites, particularly in cost sensitive applications such as those in the construction industry.

It is well known that a crack can only propagate under local tensile stress field which can be created by remote tensile load or remote compressive loads. An example of the latter can be found in shear failure or splitting failure in brittle materials [7, 8]. On the other hand, local compressive stress can stop crack propagation and oppose crack opening. The sources of local compressive stress can be from remote compressive loads or even from remote tensile loads. The latter is the subject of this study. In this letter, some preliminary results of concrete strength improvement by distributed local compressive stress zones, are reported. The local compressive stress was imposed by specially arranged steel chains under remote tensile loads. This work was initially motivated by a recent discovery of local lock-up mechanisms which account for significant improvements of toughness in brittle composites [9].

A series of steel chains (made of paper clips) was arranged in a contracted configuration illustrated in Fig. 1. Each chain is embedded in a collapsed condition, so that it must be stretched out before one chain transfers load directly to the next. A compressive zone is thus created between the heads of the approaching chains (see Fig. 1a). Each chain line is composed of 12 individual chains, creating a host of internal distributed compressive zones. As a control, another series of the same chains arranged in a fully stretched configuration was also prepared (Fig. 1b). This control group is used to contrast the effect of local compressive field on composite strength improvements, besides the steel reinforcement effect.

A weak mortar was first poured into the specimen mould (measured 12.7 mm H × 76.2 mm W × 304.8 mm L) until half full. Five chain lines (total steel volume fraction = 0.5%) were then placed in mid-position. Subsequently, the other half of the matrix was poured on top. All casting was performed under slight vibration. The composition of the matrix is listed in Table I. Specimens were demoulded after 24 h, and placed in a water tank for curing for 28 days. Specimens were removed from water 24 h prior to testing, and tested under direct tension in a servo hydraulic tester. Tensile stress-strain curves were recorded. A portable optical microscope was used *in-situ* during each loading stage.

As expected for the control with continuous steel reinforcement, a strain-hardening behaviour is observed after the first cracking strength in the tensile stress/strain curves, depicted in Fig. 2. Such pseudo

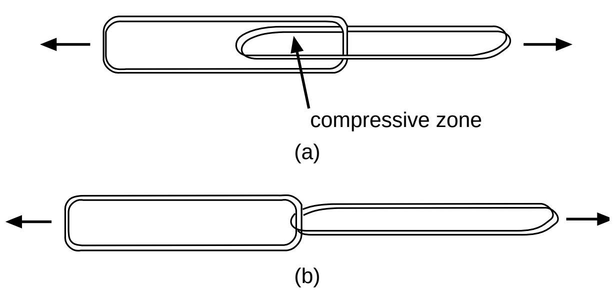

Figure 1 Schematic diagram showing two neighbouring chains in (a) contracted configuration (b) fully stretched configuration, and perpendicular to each other.

TABLE I Matrix composition (by weight)

Cement	Sand	Super plasticizer	Viscous agent	Water
1	2	0.02	0.01	0.62

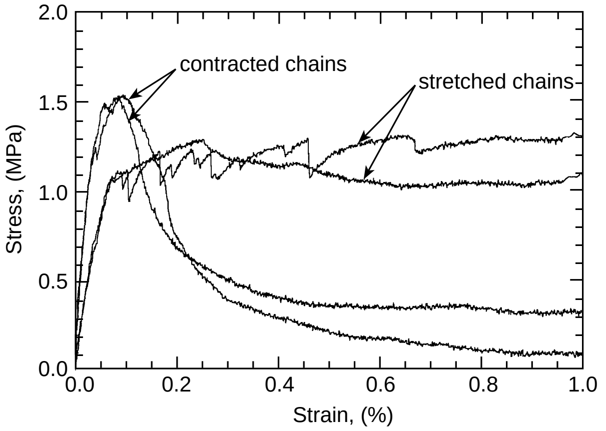

Figure 2 Tensile stress/strain curves of both fully stretched chains and contracted chains composites.

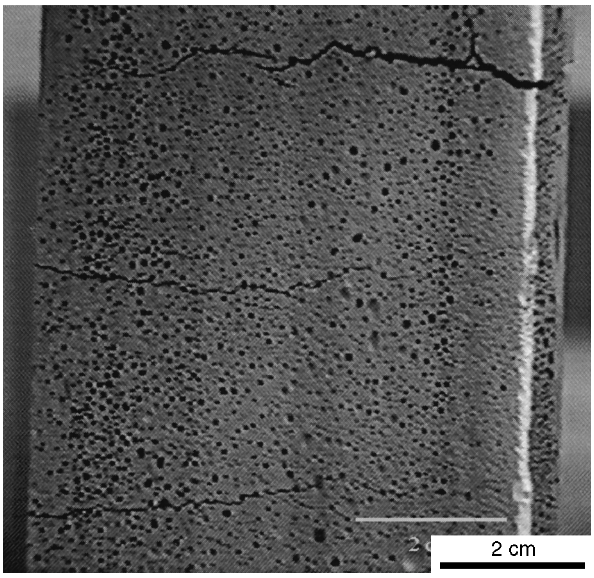

Figure 3 Multiple cracks observed in the control specimens.

strain-hardening resembling metal yielding is a result of "adequate" stress transfer from the bridging steel after the matrix cracks back onto the adjacent matrix leading to a series of multiple cracks [10]. A photograph of multiple cracks observed in these specimens is shown in Fig. 3. In Fig. 2, the tensile stress/strain curves of the composites with contracted chain reinforcement are also included. The first cracking strengths of the contracted-chain composites are 40% higher than that of the control, on the other hand, a descending branch immediately follows the peaks. The enhanced first cracking strength is due to crack arrest when propagating microcracks encounter a compressive stress field imposed by the contracted chain ends. Once a macrocrack forms, corresponding to the peak loads in the stress/strain curves, matrix spalling occurs leading to loss of lateral confinement around the compressive zones, (see Fig. 4a). Consequently, the small piece of concrete inside each compressive zone crushes (see Fig. 4b) and no further stress transfer is possible leading to a rapidly reduced descending branch in the stress/strain curves.

It has been demonstrated in this preliminary study that a deliberate distribution of internal compressive stress field in composites under remote tensile loads can significantly improve the first cracking strength of the composites due to crack arrest. The way of creating local compressive zones even under remote tension and sufficient confinement acting on the materials that underwent local compression deserves a full investigation before this phenomenon can be effectively applied in the design of composites.

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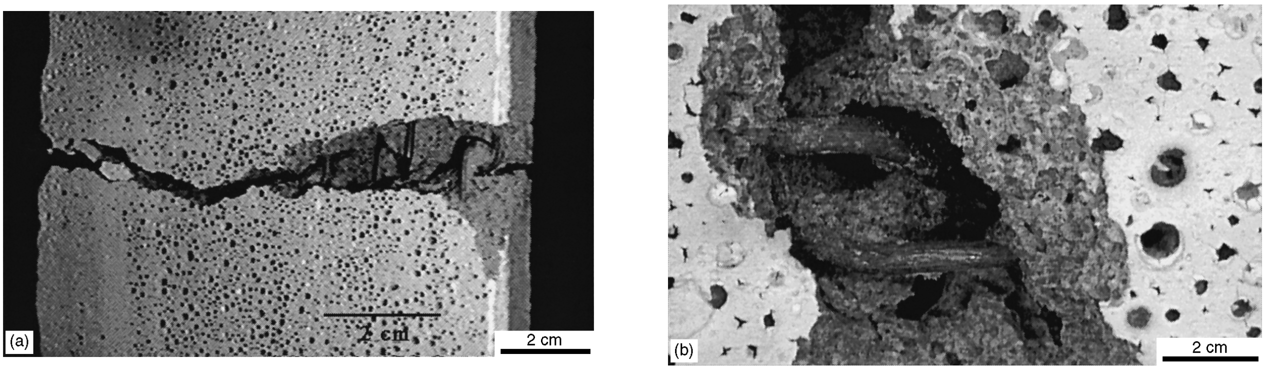

Figure 4 (a) Single macrocracks showing matrix spalling, of the contracted chain composites (b) enlarged view showing concrete crushed between two chain ends.