Behavior of High-Strength Fiber-Reinforced Concrete Beams under Cyclic Loading

by Laurent Daniel and Ahmed Loukil

This study investigated the influence of longitudinal steel ratio and steel fiber length on high-strength concrete (HSC) beams' behavior under alternate cyclic bending. The evaluation in both structural properties and cracking patterns was compared with results from an monotonic bending test. To observe the influence of fibers on deterioration of mechanical properties due to loading cycling, high-strength fiber-reinforced concrete (HSFRC) beams were tested using two fiber lengths: 30 and 60 mm. This analysis highlighted the positive effect of fibers on both the dissipated energy and the energy behavior. Within this framework, the positive effect of fibers has been underscored. The general test setup and beam cross section are described in Table 2.

INTRODUCTION

It is well-known that high-strength concrete (HSC) is a material featuring many favorable aspects, not only by virtue of its high compressive strength, but also through its ductility improvements. The mechanistic tests in the literature, however, have revealed the brittleness of HSC and the low rate of increase in tensile strength. These features reduced the use of HSC in earthquake zones as a result of recommendations of the American Concrete Institute (ACI). The introduction of fibers accounts for a significant increase in compressive strength, but also through its ductility improvements. The general test setup and beam cross section are described in Table 2.

EXPERIMENTAL PROGRAM

The general test setup and beam cross section are described in Table 2. A strain-gauged specimen was used to apply reverse loads on beams 2.75 m in length and 150 mm in cross section. A positive and negative loading direction was introduced by means of a threaded rod system linked to the beam. The span-depth ratio was chosen to obtain bending failure. To generate failure between the loading points, stirrups (diameter of 8 mm, spacing of 20 cm) were arranged outside the pure bending zone. The influence of reinforcement on beam behavior was analyzed by testing three different values for the tensile reinforcement ratio. The steel was Type FeD500 (tensile yield strength: 500 MPa).

RESEARCH SIGNIFICANCE

This study reports useful data on the application of high-strength fiber-reinforced concrete (HSFRC) in a seismically active zone. It has been shown that reverse loads involve severe bond deterioration. The control of macrocracks by fibers enhances not only the mechanical properties of high-strength concrete in tension but also the structural behavior. According to Lemaitre and Chaboche [1], mechanical properties of HSFRC, such as strength and ductility, are strongly influenced by the length of fibers: consequently, this work presents some information about structural behavior enhancement by fibers with respect to both the length of fibers and the longitudinal reinforcement ratio used. These results broaden the application of high-strength reinforced concrete structures in seismically active zones.

MATERIAL PROPERTIES

Three types of concrete were used for the purposes of this study: HSC, HSFRC with a fiber length of 30 mm (HSFRC30), and HSFRC with a fiber length of 60 mm (HSFRC60). The mixtures for these concretes are given in Table 1.

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BOND DETERIORATION UNDER REVERSE LOADS

A cyclic loading is the worst case of loading, as each concrete layer is alternately subjected to tension and compression stresses. Concrete and steel-concrete bonds are severely damaged. The bond deterioration mechanism observed by Pope [20] is described in Fig. 3(a) and relates to the typical cyclic load deflection curve presented in Fig. 4, which displays the following sequence.

REFERENCES

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New crack (HSFRC 30 beam).

100
-40
80
80
40
0

Negative load lag:
-14 -10 -8 0

Tensile (mm)

The load-deflection curve is regulated both by the strain of tensile bars and by the strain of the compressive connection between lugs and concrete (Fig. 3(c)). The generated due to compressive stresses of the bars, which may explain the pinching of the curves during fonm

The minimal and maximal spacings measured in static tests are close to those obtained by Maurel14 on beams with spacing of 5 cm and maximal spacing of 12.5 cm). The

Cracking degrades the steel-concrete bond. As long as the load-deflection envelope curves:

The measure of the crack width, however, was not recorded during service loads, their bridge effect allows an increase of the main crack width during the failure stage. The measure of the crack width, however, was not recorded due to the difficulties induced by both alternate loads and continuous measurement.

comparision between monotonlic and cyclic tests.

To measure the influence of alternate loads on structural properties, two static tests were carried out on HSC beams with p = 0.97% and p = 1.52%, respectively. The analysis focused on both the cracking pattern and the load-deflection curves.

Cracking pattern

The expansion of the cracking zone can be observed in Fig. 6(a) and (b). The reverse loads prevent the concrete from crushing, but the concrete propagates throughout the depth over a wider zone. Moreover, a greater number of horizontal cracks are located at the level of the steel bars, thereby demonstrating the severity of steel-concrete bond deterioration.

The minimal and maximal spacings measured in static tests are close to those obtained by Mineur14 on beams with a similar cross section and a shear span of 0.8 m (minimal spacing of 5 cm and maximal spacing of 12.5 cm). The longitudinal steel ratio seems to have little influence on the spacing of cracks. The cyclic tests, however, show an increase in the spacing of cracks within the shear zone, and thus, an increase in maximal spacing. This finding can be explained by the different stages of the cracking process. At first, bending cracks occur with low structural damage, and a similar cracking development to static test is denoted. Afterwards, under alternate loads, steel-concrete debonding reduces the rate of occurrence of transverse cracks while inducing horizontal cracking.

Load-deflection curves

As a means of comparing tests under monotonic and cyclic loads, average envelope curves have been used in the cyclic cases. One example of such an envelope curve is drawn in Fig. 4. A comparison of different curves is provided in Fig. 6, and some mechanical properties are given in Table 4.

Before the peak load, it has been noted that alternate loading does not change the secant stiffness of the HSC beams, but does induce a decrease in maximal load capacity by approximately 10%.

Beyond the peak load, the slope of the cyclic curve drops sharply and accounts for the decrease in structural ductility. This ductility is defined as the ratio of ultimate deflection to the deflection at the peak load ∆/∆max. This study of such a structural ductility was the topic of another paper.15 The ultimate deflection corresponds to the deflection measured at 85% of the peak load. For p = 0.97%, the cyclic loading decreases the ductility by 36%. For p = 1.52%, data acquisition was not performed beyond the postpeak, but it was thought that the loss in ductility would not be so high as a result of the greater brittleness of beams exhibited by the increase of tensile reinforcement under monotonic loading. Cracking degrades the steel-concrete bond. As long as the number of cracks increases, the force redistribution in the compressive zone is more effective, the structural behavior remains similar. Under alternate stresses, both the cyclic softening of materials and the time lag of the force redistribution in the compressive zone due to crack closure lead to a steep postpeak branch.

INFLUENCE OF FIBERS ON CYCLIC BEHAVIOR

The structural tests with fiber reinforced concrete (FRC) have demonstrated the influence of the steel reinforcement ratio on fiber efficiency. For this reason, three values of the longitudinal steel ratio have been used: p = 0.55, 0.97, and 1.52%. Both the concentration and the fiber ratio of fibers are also used as efficiency factors. It has therefore been decided to use a constant fiber volume of 1% with an E12 ratio of 80. It should be pointed out that the size of the structure is another important factor in regard to the structural efficiency of the FRC, however, the size effect has not been raised herein since all beam specimens have the same height. In this paper, the influence of fibers has focused on cracking pattern, strength deterioration, the load-deflection envelope curves, and the cumulative damage capacity.

Influence on apparent cracking

The influence of fibers on the apparent cracking can be visualized in Fig. 7(a) and (b). The influence of fibers on cracking induced by steel-concrete debonding. Some isolated cracks can be noted, however, which suggests the random bridging effect of fibers inside the cross sections.

Influence on load-deflection envelope curves

Figure 8 presents cyclic envelope curves that resulted by taking an average of positive and negative envelope curves. The deflection gain at the peak load is insignificant; the curve was thus drawn with respect to the peak deflection relative to the peak deflection, and correspond to the definition of structural ductility. Three stages can be distinguished: the first is a structural behavior without any damage, as char-
Table 5—Results of tested beams

| Vol. of | P1 | P2 | Fpeak | Fpeak | Epeak | Kpeak | Kinitial |
|---------|----|----|-------|-------|-------|-------|---------|
| fibers  | kN  | kN  | kN    | kN    | kN/mm | kN/mm | kN/mm   |
| L-10    | 95  | 24  | 18.9  | 58.5  | 9.2   | 6.3   | 1.52    |
| L-30    | 110 | 48  | 20.1  | 65.6  | 9.9   | 8.6   | 1.31    |
| M-30    | 112 | 60  | 20.9  | 115.6 | 11.0  | 10.2  | 1.22    |
| L-60    | 113 | 63  | 20.9  | 134.2 | 12.1  | 10.7  | 1.20    |

M-ref: secant initial stiffness; and K_{ref} = secant stiffness at peak load.

Fig. 7—Bending and shear cracks on M-series.

Fig. 8—Load-deflection envelopes on L-, M-, and H-series.

Fig. 9—Fibers replacing reinforcing capacity (comparison of L-, L-60, and M-ref).

Influence on cumulative dissipated energy

Measuring ductility is not only a motivating factor for investigating behavior during the postpeak phase. When earthquakes occur, energy gets injected into the structure and then has to be dissipated for safety reasons. According to this setup, the behavior of fibers inside the matrix acts as a dissipative mechanism. The measurement and contribution to this action could thus become a good efficiency index independently from structural ductility considerations.

During cyclic tests on structures, dissipative mechanisms are frequently encountered and must be distinguished to determine the action of fibers on the dissipated energy (Eq. (1)). In fact, a principal energy $E_p$ is injected into the structure, composed of beam-column and supports. One component of this energy is redistributed into the soil $E_s$, while the other is used by the structure over the elastic $E_{el}$ and inelastic $E_{in}$ domains. The first component $E_p$ represents the energy necessary both for beam displacement (kinematics energy $E_k$) and for elastic strain $E_e$. The latter component $E_e$ includes damping energy and hysteretic energy.

$$E_p = E_s + E_{el} + E_{in}$$

Structural collapse corresponds herein to the case observed when the structure is no longer able to dissipate the accumulated energy. It is therefore important to increase the energy storage capability in the elastic domain in the energy dissipation in the inelastic domain. For the first aforementioned reason, the use of HSC increases structural stiffness due to the contribution of high compressive strength as well as to the improvement of the steel-concrete bond. The low tensile strength and brittle nature of concrete, however, prevent the possibility of increasing energy in the inelastic domain. Adding fibers inside the high-strength limits concrete damage in the elastic domain, and results in energy dissipation in the inelastic domain due to the strain and fiber slip inside the matrix.

The dissipated energy during a loading cycle was determined by computing the hysteretic area of the loop. The increase of dissipated energy during cycles at similar displacement amplitudes is low. It was thereby assumed that the contribution of fibers is concentrated during the first cycle of each displacement amplitude. The computation of primary dissipated energy was carried out up until total collapse (Fig. 10).

For L-series—Fibers increase the capacity of energy up until collapse. The gain provided by the longest fibers, compared with the shorter ones, is observed at the end of the test for a normalized deflection of greater than 1.4. The maximal dissipated energy increases by 45% for HSIPFCO (1490 KNm) with respect to HSC, while for HSIPFCO it increases by only 13%.

For M-series—Only the HSIPFCO increases the dissipation of energy up until collapse, with an increase in ultimate dissipation (2240 KNm) of 41% with respect to HSC. The behavior of HSIPFCO is similar to that of HSC, with a low increase in dissipated energy over the postpeak zone. Furthermore, the maximal value is 26% less than that of HSC, which highlights the low effectiveness of short fibers.

For H-series—A reduction in the improvement of long fibers is noted since the maximal energy with respect to HSC increases by 28%. HSIPFCO does not show good behavior, as the increase in dissipated energy remains less than that of the HSC beam during the entire postpeak stage.

There were not enough repetitive tests to draw firm conclusions, but some trends could be mentioned. It seems that...
Overall, to overcome this constraint, a new damage index (Eq. (8)), based on the expression of Sadeghi's index (Eq. (6)), has been developed. A strain factor $a_i$ (Eq. (9)) is introduced for the dissipated energy of each first cycle $E_{i1}$ to stand for the secant stiffness deterioration with respect to the peak load. The damage induced by successive cycles of similar displacement amplitude is attenuated by a fatigue factor $\lambda_i$ (Eq. (10)) related to the strength deterioration with respect to the first cycle. The energy summation is normalized by the total amount of energy dissipated by each first cycle $E_{I1}$. The tensile reinforcement ratio $\rho$ is introduced to take into account the difference in energy behavior with increasing tensile reinforcement. The postpeak number is computed to yield an index value close to that of the HSC beams.

**CONCLUSIONS**

The aim of this study has been to investigate the influence of fibers on the behavior of HSFRC beams under cyclic bending. The severe concrete damage due to alternate loading induces a loss in both maximal load capacity and ductility. This degradation suggests that the use of fibers can be efficient to prevent an early emergence of macrocracks during the prepeak stage. Fibers induce an increase in beam structural stiffness up to the peak load. For a tensile reinforcement ratio of 0.5, the HSFRC exhibits a stress similar to that of an HSC beam with a tensile reinforcement ratio of 0.97%. Nevertheless, the fibers have no influence on strength deterioration during loading cycles at a given displacement. In the postpeak stage, the computation of ductility shows the difficulty involved in improving behavior. The increase in loading capacity of HSFRC beams leads to a steeper slope of the postpeak branch. Within an energy-based framework, however, and particularly so in the case of earthquake zones, the insertion of long fibers enhances the energy dissipation over both the elastic and inelastic domains for all longitudinal reinforcement ratios; with regard to the 30 mm fibers, however, enhanced energy dissipation only occurs for lower ratios. With respect to energy dissipation alone, however, 30 mm fibers may be recommended for lower reinforcement ratios. The effect of the cumulative damage capacity is positive for 60 mm fibers, with an efficiency limit for $\rho = 1.52%$. These findings have raised the possibility of using the HSFRC in small-sized structures (low heights or low reinforcement ratios) in earthquake zones to increase the
mechanical postpeak properties and energy dissipation in the inelastic domain.

**NOTATION**

- $D_i$: damage index
- $d_f$: fiber diameter
- $E_i$: hysteretic energy of one cycle
- $F_i$: first cracking load
- $F_{\text{max}}$: peak load or maximal load
- $K_{S\text{max}}$: secant structural stiffness at peak load
- $l$: fiber length
- $\alpha$: strain factor
- $\delta_{F\text{max}}$: deflection at peak load
- $\lambda$: fatigue factor
- $\rho$: longitudinal reinforcement ratio

**CONVERSION FACTORS**

- 1 mm = 0.039 in.
- 1 kN = 0.2248 kips
- 1 MPa = 145 psi

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