STEEL FIBROUS CONCRETE UNDER SEISMIC LOADING[a]

Levon Minnetyan[1], and Gordon B. Batson[2]

Department of Civil and Environmental Engineering
Clarkson College of Technology
Potsdam, New York 13676
USA

1. INTRODUCTION

Steel fibrous reinforced concrete is a structural material that has been under development in the last two decades [1,2]. Investigations into the effects on the strength, stiffness, and ductility properties of steel fiber concrete have included static loading, static cyclic loading, impact loading and low amplitude dynamic fatigue loading experiments [3,4,5,6]. Results from these investigations have shown that the addition of fibers to concrete mixes can significantly improve the performance of this material. The improvements on ductility are especially significant under dynamic loads. One area where the potential advantage of steel fiber reinforced concrete is foreseen is that of earthquake resistant design. Conventional reinforced concrete is often unable to maintain its stiffness under dynamic loads imposed by seismic conditions. Steel fibers have been shown to improve ductility and toughness properties of concrete mixes, provide higher first crack tensile strength and help to retard spalling under impulsive loading conditions. These characteristics can lead to better earthquake resistant designs. Steel fiber concrete can be used to reduce the required amounts of steel bar reinforcement at critical regions of the structure. Congestion with conventional bar reinforcements is known to be one of the major causes of bond deterioration at a critical region. In order that steel fiber concrete be considered an appropriate alternative for seismic design its nonlinear constitutive properties under seismic loading conditions must be known. To determine these characteristics a study of the behavior of steel fiber reinforced concrete when subjected to high intensity dynamic loadings at typical seismic conditions has been undertaken. This study addresses the question of determining the contribution of steel fibers to the dynamic stiffness and strength of reinforced concrete members; including the effects of loading history and cracking. An experimental research program is currently in progress with the objective of the identification of an appropriate mathematical model that can be used in earthquake resistant design.

2. INELASTIC RESPONSE UNDER SEISMIC LOADING

All reinforced concrete structures will crack at some intensity of static and/or dynamic loading. Serviceability of a structure should be maintained under static design loads and moderate seismic loads. It is not economically feasible to design a structure to remain serviceable under very intense seismic forces. However, safety against collapse of a structure should still be maintained under most intense seismic loads. To predict the performance of structures under seismic conditions we need, among other information, the stiffness, damping, and strength properties of structural members. The determination of dynamic resistance characteristics of cracked sections is essential for the assessment of the effectiveness of steel fibrous concrete for aseismic design of

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[1] Assistant Professor

[2] Professor

structures.

The causes of cracking and the resulting inelastic effects on the constitutive relations of reinforced concrete have been investigated both experimentally and analytically [7]. It has been demonstrated that much of the inelastic action of a structure subjected to seismic loading occurs in the joint regions where large moment reversals take place and bond slip occurs [8]. Parallel to dynamic experimentation, pseudo-dynamic cyclic tests on beam-column joints reveal that after the establishment of a plastic hinge, flexural strength is mostly conserved by numerous hysteretic load cycles although the dynamic stiffness rapidly deteriorates [9].

The nonlinear inelastic seismic analysis of a reinforced concrete structure is usually based on a bilinear yield mechanism mode. This model assumes that a bilinear hinge will develop at the end of a frame member when the moment at that point exceeds the yield moment of the section. This bilinear behavior mechanism usually allows for about 90% to 95% reduction in stiffness of the section during yielding and provides a hysteretic energy loss mechanism in the joint. When used with provisions for global stiffness degradation after yielding at joints, the bilinear yield mechanism model has rendered a fairly close description of the actual structural response for typical test cases [10]. However, general stiffness properties of a structure change in a very complex fashion during the dynamic response and it is difficult to establish a truly general stiffness degradation model which will be applicable to all dynamic loading situations.

Further experimental and analytical research is needed to study the behavior of reinforced concrete sections under high intensity dynamic loads to assess the feasibility of alternative forms of reinforced concrete such as steel fiber concrete in aseismic design. The flexural behavior of a cracked section during the development of a plastic hinge is of primary interest.

In the past, the free vibration response of a cracked, reinforced concrete beam has been investigated analytically assuming a reduced flexural rigidity for the cracked part [11]. It is noted that this reduced flexural stiffness depends upon the beam cross-section, number and size of cracks, percentage and placement of reinforcement and other factors. Furthermore the dynamic flexural stiffness of the cracked portion is a function of both time and position of the beam. The theoretical results indicate the response of the system to be a nonlinear type with a soft characteristic. However, the basic assumptions for the formulation of the flexural stiffness are not explained. Neither is the stiffness reduction given explicitly for individual cases nor is there an indication how it can be determined for a specific cracked beam.

Theoretical and experimental investigations of dynamic properties of uncracked reinforced concrete beams are discussed in reference [12]. The authors of reference [12] acknowledge to have also conducted dynamic experiments with cracked beams but that they could find "no definite correlation" between the dynamic responses of cracked and uncracked beams.

Fatigue experiments with steel fibrous reinforced concrete beams have assessed the relative effects of fiber concentration, fiber shape, load intensity, forcing frequency and load reversal on the fatigue life of beams [6, 13]. However, these dynamic experiments have not included the hign intensity loads that would represent seismic effects.

Dynamic characteristics of reinforced concrete beam-column specimens were measured for various levels of cracking in reference [14]. This reference concludes that natural frequencies will be lower after cracking. This observation is generally correct but incomplete. The natural frequency of a cracked structure will depend on the vibration amplitude as well as the amount of cracking and crack patterns.

3. CRACKED BEAM - A CONSERVATIVE TREATMENT

Let us consider the free vibration response of the first mode of a simply supported homogeneous conservative beam of density ρ, elastic modulus E, with a vertical crack of length d_c at its midspan as shown in Fig. 1-a. For dimensional simplicity the beam is assumed to have a rectangular cross-section of unit width. The crack will be open or closed during different stages of a vibration period depending upon the deflected position of the beam (Figures 1-b, 1-c).

If the free vibration amplitude α is smaller than the static deflection δ of the cracked beam under its self weight, the crack will always stay open and there will be a constant natural frequency lower than that of the uncracked beam but still independent of the vibration amplitude. The energy or the integral curve [15] in the displacement-velocity plane will be a complete ellipse as S_1 in Fig. 2, with gravitational datum corresponding to the static deflection δ of the cracked beam. On the other hand, if α is greater than δ the energy curve will follow S_2 for portion of the vibration period while the crack is open; however, a transition will occur at $y = -\delta$ when the crack will close and the energy curve will follow the ellipse S_2^* beginning at point A until the crack opens again at point B. The energy curve S_2^* has a higher gravitational datum corresponding to the static deflection of the uncracked beam, but it has an equally lower elastic potential datum such that conservation of energy is satisfied. The time contribution of the followed path A-B of S_2^* is less than the time subtracted by deleting corresponding part of S_2. The result is a decrease in the free vibration period T or increase in the free fibration frequency ω of the cracked beam; indicating a hard characteristic for this conservative dynamic system. Numerical results of amplitude versus natural frequency computed by the methods described in reference [16] are plotted for three different crack depths in Fig. 3. For actual cracked reinforced concrete beams, nonlinear material behavior will soften the vibration characteristics such that a frequency-amplitude relationship may look as shown in Fig. 4; still partially contradicting the soft nonlinear characteristic assumptions of references [11] and [14].

The phenomenon described above is very common during actual seismic loading of structures. In some publications it is referred to as "a greater elastic response due to a lengthening period" [17]. This observation seems to agree with our hypothetical amplitude frequency relationship depicted in Fig. 4. If Fig. 4 were to be obtained from actual experiments it could be interpreted as a close-to-linear behavior with possible scattering of data. However, linear superposition methods are not valid in this case since apparent linear behavior for a specific cracked inelastic beam will be due to the contribution of opposing nonlinear effects. Consequently, the influence of opening and closing of cracks and the effect of material nonlinearities due to high stresses at cracked regions must be taken into account simultaneously to interpret the true implications of experiments. The closing of cracks during a seismic acceleration period of long duration will generate an impulsive load on the structure and actually determine the failure direction of the entire frame. This behavior has been observed in most earthquakes and described as "pumping" by Newmark [18]. Pumping is due to a partial ultraharmonic excitation of a structural system with asymmetrical nonlinear vibration characteristics. Pumping will influence the sense for the P-Δ effect which will eventually impose the collapse mechanism on the structure [19].

4. CURRENT EXPERIMENTAL SCOPE

Within the experimental portion of the present investigation, beam

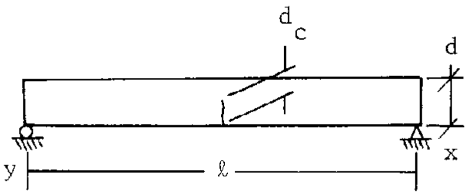


Fig. 1-a. Beam with Vertical Crack at Midspan

Fig. 1-b. Downward Deflection - Crack is Open

Fig. 1-c. Upward Deflection - Crack is Closed

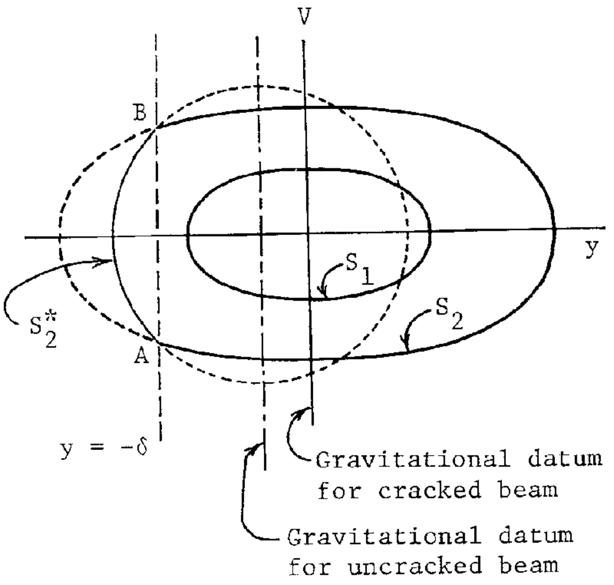


Fig. 2. Energy Curves for Conservative Cracked Beam

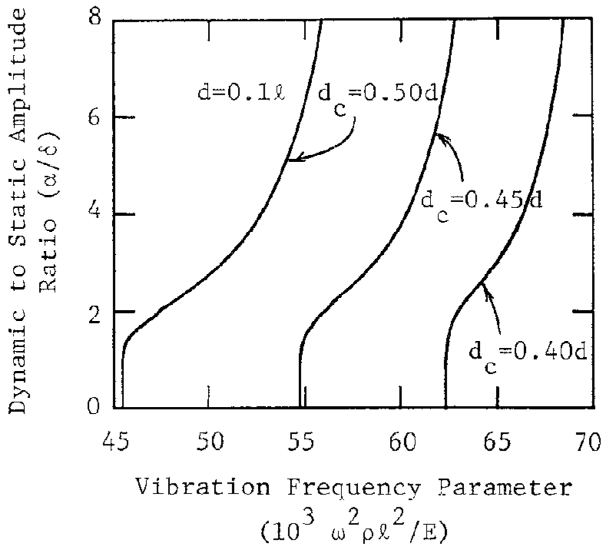


Fig. 3. Amplitude-Frequency Relationships for Conservative Cracked Beam

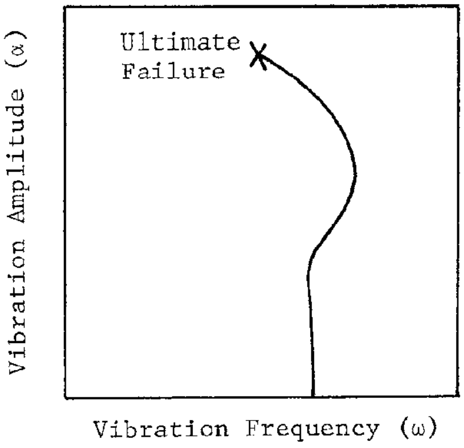
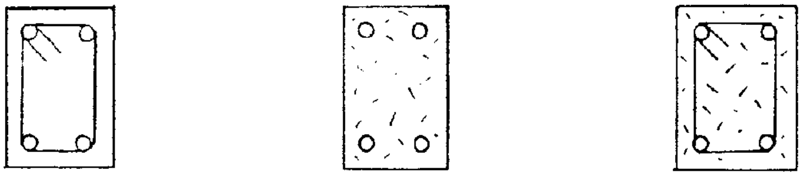


Fig. 4. Amplitude-Frequency Relationship for a Cracked Beam with Material Nonlinearities

specimens of two different lengths with three types of reinforcement for each length are fabricated and subjected to dynamic loads. To keep the material and equipment cost down relatively small beam cross-sections are used for the experiments. A typical beam cross-section measures six inches deep and four inches wide (152 mm x 102 mm). It has been shown that flexural tensile strength is not significantly altered by size effects when specimen depth is six inches or greater [20]. However, shear strength may be altered by size of beam as shown by prototype beam tests by G. Williamson at CERL [21]. The difference in failure mode of prototype used by Williamson and small size beams tested by Batson et al. [6] is an important point under investigation in the current project.

The steel fibers used are all of the same type with hooked or bent ends and are supplied in water soluble glued bundles. The amount of steel fibers is constant at 3/4 percent by volume for all steel fibrous concrete mixes. The maximum aggregate size is limited to 3/8 in. (9.5 mm) peastone regardless of beam size. This is to assure effective crack arrest by the close spacing of the steel fibers.

To date thirty-three long span beams and thirty-three short span beams have been tested. The long span beams measure 6 in. x 4 in. x 8 ft. (152 mm x 102 mm x 2.4 m) and include three reinforcement types shown in Fig. 5.



2#4 T&B
standard shear
reinforcement
without fiber

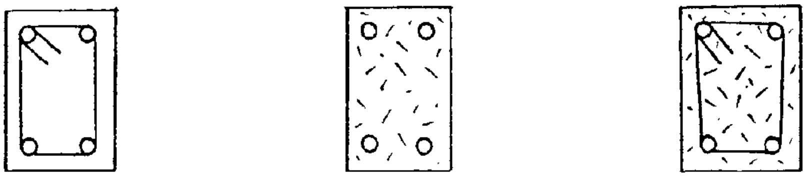
Type L1

2#4 T&B
without shear
reinforcement
with fiber
(∿ 3/4% by Vol.)

L2

2#4 T&B
with shear
reinforcement
and with fiber
(∿ 3/4% by Vol.)

L3



2#3 T&B
standard shear
reinforcement
without fiber

Type S1

2#3 T&B
without shear
reinforcement
with fiber
(∿ 3/4% by Vol.)

S2

2#3 T&B
with shear
reinforcement
and with fiber
(∿ 3/4% by Vol.)

S3

Fig. 5. Types of Reinforcement

These reinforcement types include longitudinal steel with standard shear reinforcement, longitudinal steel with fibers but without standard shear reinforcement, and longitudinal steel with both fibers and standard shear reinforcement. Building codes do not at this time recognize fiber reinforcement for resisting shear. However, the steel fibrous types without standard shear reinforcement are also included to assess the trade-off between stirrups and fibers in effectiveness to resist shear. The short span beams have the same cross-sections but are fabricated merely 4 ft. (1.22 m) long. Eleven specimens of each reinforcement type have been tested. From each type three beams are tested under full dynamic cyclic loading at 1.0 H_z loading frequency. Three other specimens are tested under the same loading magnitude but at a reduced rate of 0.2 H_z. The remaining beams are tested under partial moment reversal, similarly at 1.0 H_z and 0.2 H_z frequencies. An electrohydraulic ram capable of sustaining a sinusoidal varying force is used to excite the beam specimens which are dynamically simply supported and loaded at midspan. Beam deflections are measured by the use of Linear Variable Displacement Transducers (LVDT's), placed along the beam. A microcomputer is used to control the testing and to accumulate the experimental data in digital format [22].

5. RESULTS

At present, the outcome of sixty-six dynamic experiments can be best summarized in terms of the average relative performance of the different reinforcement types. In the case of long span beams the flexural tensile stresses were more significant compared to shear effects. All long span beams failed gradually as the dynamic stiffness was lost over many cycles of loading. The relative performance of these beams is summarized in Table 1. The three different types of long beams are loaded under the same dynamic loadings. Loading is sufficiently intense to start cracks in the specimens with the first cycle of loading. Initial stiffness is defined as the ratio of force to displacement at the first load peak. Relative initial stiffness is the initial stiffness normalized with respect to that of a conventionally reinforced beam. It is observed, from Table 1, that the average relative initial stiffness is about the same for all three types of long beams. Dynamic ductility is defined as the number of cycles before a "failed" deformation state is reached. At the slow loading rate of 0.2 H_z the improvement in dynamic ductility with the addition of fibers is very small. However, at the faster loading rate of 1.0 H_z the fibers have a more significant influence. The most interesting result is that fibers by themselves are more effective than having both the same amount of fibers and stirrups when the loading is applied at 1.0 H_z. It is also noteworthy to observe the very significant dependence of dynamic ductility on the loading rate for all types of reinforcement.

Table 1 Long Beams

Type of Shear Reinforcement	Average Relative Initial Stiffness	Average Relative Dynamic Ductility	
		0.2 H_z	1.0 H_z
Conventional Stirrups	1.00	1.0	8.8
Fibers	1.00	1.1	81
Stirrups and Fibers	1.04	3.2	36

Table 2 summarizes the relative performance of different reinforcement types for the short span beams. For these short beams the shear effects control the deformations, cracking, and the failure mode of the beams. Unlike the long beams, the short beams usually fail in a sudden "catastrophic" manner without much warning. Table 2 indicates that fibers are relatively more effective as shear reinforcement for the shorter beams under significant shear loading. It is also observed that the loading rate effects are not as dramatic when the fibers are used as shear reinforcement in short beams. Another difference from the long beams is that in the case of short beams, the shear reinforcement type affects the initial stiffness. Also, experimental data indicates that the short beams with only conventional stirrup type shear reinforcement deteriorate significantly during the first three cycles of loading, whereas the steel fibrous short beams retain the dynamic stiffness over a much larger number of loading cycles.

Table 2 Short Beams

Type of Shear Reinforcement	Average Relative Initial Stiffness	Average Relative Dynamic Ductility	
		$0.2\ H_z$	$1.0\ H_z$
Conventional Stirrups	1.00	1.0	5.0
Fibers	1.26	27	45
Stirrups and Fibers	1.19	8.5	11

6. CONCLUSIONS

In summary, from the current experimental results, it may be deduced that replacing the conventional shear reinforcement with steel fibers at high shear regions will improve the dynamic stiffness by 26 percent and the dynamic ductility is increased nine fold at 0.2 H_z frequency of dynamic loading. However, if the fibers are added to conventional stirrups, then the dynamic stiffness increases only 19 percent and the dynamic ductility merely doubles. At first glance these results would indicate that stirrups should be excluded from steel fibrous concrete reinforcement. However, it should be noted that no axial forces are considered in the present investigation. It is believed that stirrups will still be necessary to provide the confining reinforcement when axial compression forces are added to shear and bending effects. Another reason to include stirrups with steel fibrous concrete members is to soften the final failure behavior of these structural members. Experimental beams with only steel fibers had the best stiffness characteristics and lasted through the largest number of dynamic loading cycles. However, their failure was precipitated very suddenly and without much advance warning during loading of short beams. Including also the conventional stirrups in addition to steel fibers softens the failure pattern at a reasonable cost of somewhat reduced dynamic stiffness and ductility.

Finally, it is relevant to note that the present experimental investigation is scheduled to continue with additional types of reinforcement and prototype sizes of beams. In addition, a system identification program is currently in progress to identify a practical mathematical model for the behavior of steel fibrous reinforced concrete beams to be used as a tool in earthquake resistant design with this material.

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