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Steel fiber as replacement of minimum shear reinforcement for one-way thick bridge slab

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HIGHLIGHTS

- An alternative solution to the use of minimum shear reinforcement in thick slab.
- Performance evaluation of SFRC thick slab with and without prestressing.
- The effect of stirrups, fibers and prestress on the shear and ductility performance.
- A procedure for predicting shear resistance of SFRC thick beam.

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ABSTRACT

This paper evaluates the possibility of replacing minimum shear reinforcement by steel fibers in both prestressed and non-prestressed thick concrete slab. Due to brittle behavior of plain concrete in tension, shear failure of thick slab is generally catastrophic. The use of minimum shear reinforcement is recommended in many instances to avoid such failure. This paper presents an alternative solution realising that the use of optimum steel fibers can give ductility performance equivalent to the slab with minimum shear reinforcement. To evaluate the effect of steel fibers on shear performance, eight full-scale tests are carried out. The influence of fibers on shear performance is evaluated and its potential to replace the minimum transverse steel of thick slab is discussed. Finally a procedure for predicting the shear capacity of such slab is presented.

1. Introduction

In many one-way bridge slab, the width and height of the concrete section will be sufficiently large so that one way shear demand can be satisfied by the concrete alone. This configuration would avoid the labor, material cost associated with the introduction of shear reinforcement in construction. This structural configuration has proven very economical and attractive in constructing bridge slabs in many countries, especially in North America. However, research has established a size effect in the shear strength of RC members without shear reinforcement or fibers, where the shear resistance decreases with an increase in member depth [1,2]. Furthermore, recent research has highlighted the difficulty associated with the accurate prediction in assessing the shear capacity of large thick slab without web reinforcement using ACI code [3]. Due to limited size range of the members studied, the empirically derived ACI 318 expression was not able to capture the size effect of shear.

If the shear design of the slab is inaccurate, and the shear capacity is only two-third of that which is required, a brittle shear failure would occur with no prior warning, resulting in the collapse of the structure and possibly great loss of life. Thus, it has been recommended that stirrups be included in all large members like bridge slab to mitigate size effect in shear and to enhance the member ductility [2]. Both the AASHTO LRFD [4] and CAN/CSA S6 [5] codes assume that the introduction of minimum web reinforcement mitigates the size effect in shear. This is a variation from traditional approach to deep slab design where the thickness of the slab was often determined to avoid the use of shear reinforcement. The introduction of shear reinforcement has significant influence on the cost of such structures, both in terms of labor and material. As a consequence, a structural type that has proven very economical, durable and easy to construct may be less attractive now.

Research in the past has established the potential uses of fiber reinforcement in enhancing the shear capacity of reinforced or prestressed concrete beams [6–9]. The use of steel fibers in concrete

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Notation

b_v	effective web width
d_v	effective shear depth
ε_x	longitudinal strain at mid depth
A_v	area of shear reinforcement
A_f	area of fiber
V_c	shear capacity of concrete
V_s	shear capacity of stirrups
V_f	fiber contribution to shear capacity
v_f	volume fraction of fiber
s	stirrup spacing
s_{ze}	crack spacing parameter
ϕ	capacity reduction factor
β	parameter that model the ability of cracked concrete to transfer shear
θ	angle of inclination
α	fiber orientation factor
η	fiber embedding length factor
$f_c^/$	compressive strength of concrete
f_y	yield strength of steel
f_{cr}	cracking strength of concrete
τ	interfacial bond stress
N_P	total pull-out force of fiber
d_f	diameter of fiber
L_f	length of fiber

increases ultimate shear strength, increases stiffness and transforms failure mode from brittle shear failures into more ductile failures. Furthermore, fiber reinforced concrete shows better fatigue and durability properties [10]. The literature describes numerous studies of rectangular fiber reinforced beams without stirrups [6–9,11–22]. Baston et al. [6] performed the first large experimental study of such beams. Subsequent investigation on normal strength and high strength concrete confirmed the effectiveness of adding steel fiber and identified key parameters that affect the shear strength. In 2006, Majdzadeh et al. [18] has investigated the influence of both steel and synthetic fibers of variable volume fraction on the shear capacity of reinforced concrete beam. It was observed that 1% volume fraction of fiber gives optimum enhancement of the shear capacity and no benefits were noted when the volume fraction increased beyond 1%. It was also observed that for a given volume fraction, steel fibers are more efficient than the tested synthetic fibers. Thus, using of optimum proportion of steel fibers in concrete that can replace the minimum shear reinforcement is interesting to provide a cost effective solution.

It should however, be noted, that majority of the past research on SFRC beams reported in the literature are on specimens of small to medium size. Most of the SFRC beams depth tested earlier fall within the range of 100–300 mm, with only a small number of test specimens having depth greater than 300 mm [19]. Furthermore, experimental data on thick beam with fiber and prestress which is very common in bridge slab is very limited in literature. The objective of this paper is to propose an alternative solution to the design approach of thick slab requested by codes (AASHTO LRFD and CSA), by using steel fibers in concrete that would provide a similar ductile behavior to that of slab with minimum shear reinforcement. In this research, an experimental program is carried out that consists of eight (8) shear tests on reinforced concrete and fiber reinforced concrete slabs. As prestress has a favorable effect to limit the crack opening, and as structural slabs are often post-tensioned, it was deemed interesting to include prestressing as a variable for this study. Therefore, four (4) non prestressed, and four (4) prestressed thick slabs are tested in this study. From the study, the contribution of fibers on ductility and shear performance are evaluated and the potential of steel fiber to replace the minimum shear reinforcement of thick slabs are discussed. Furthermore, a procedure for predicting the shear capacity of SFRC thick slab is also presented.

2. Experimental investigation

2.1. Test program

Table 1 shows the test program that was designed to investigate the ability of steel fiber reinforced concrete to replace the minimum shear reinforcement in structural deep bridge slabs. A total of eight full-scale tests were carried out in the laboratory. To reduce the number of specimens to be constructed, each specimen was designed so that both sides of the specimens could be tested. Hence, four (4) specimens were constructed. All the slabs with fiber reinforced concrete were tested twice to evaluate the variability of the results. The tests on slabs with regular concrete are conventional and it was not deemed necessary to repeat such tests. The first two specimens (1 and 2) of Table 1 are reinforced concrete slabs. One side of specimen 1 has no shear reinforcement whereas the other side contains minimum shear reinforcement in accordance with CAN/CSA S6 and AASHTO LRFD code [4,5]. Specimen 2 is designed to see the effect of steel fiber on RC thick slab. As structural bridge slabs are often post-tensioned; the rest two specimens of Table 1 (specimen 3 and 4) were prestressed slab. The variation of fiber content and shear reinforcement in these prestressed slabs was similar to that of reinforced concrete specimens. Thus, the experimental program consists of three variables: (i) presence of minimum shear reinforcement, (ii) use of steel fiber reinforced concrete; and (iii) prestress or no prestress.

2.2. Materials properties

2.2.1. Concrete mix

The objective of the mix was to provide a regular concrete with a specified strength of 35 MPa. For this purpose a target strength of 43 MPa (8 MPa larger than 35 MPa) was chosen. The cement that was used in mix contains about 8% of silica fumes. The fiber concrete mix was designed so as to obtain the same strength as the regular concrete. Hence, starting from the same row materials, in order to compensate for the inclusion of fiber, slightly more water and cement is added while quantities of sand and aggregates are reduced. The steel fibers used in concrete were 60 mm long and 0.9 mm in diameter with hooked end as shown in Fig. 1. The tensile strength of this fiber was 1035 MPa. After some preliminary calculation, it was identified that 0.75% (60 kg/m^3) is the minimum amount of fiber that is effective in replacing the minimum shear reinforcement. Table 2 shows the amount of component materials used for the production of one cubic meter of conventional concrete and fiber reinforced concrete.

2.2.2. Strength of concrete

To evaluate the strength of concrete, both the regular and fiber reinforced concrete were tested in the laboratory. For the compressive strength of concrete, 100 × 200 mm cylinders were casted from the same concrete of slabs, and strengths were measured at the same date as the testing of slab. To evaluate the tensile strength 180 × 180 × 700 mm prisms were casted following the ASTM Standard 1609 [23]. The dimension of the prisms was determined to be 3 times the length of the fiber as recommended by ASTM 1609. Loading was applied in displacement control so as to capture the post-peak behavior. Table 3 shows the compressive and flexural tensile strength of concrete for the four full-scale slab specimens.

It can be seen from Table 3 that the observed concrete strength is between 48 MPa and 50 MPa at ages ranging from 65 to 68 days which is consistent to what would be obtained for this type of concrete in practice. It is interesting to note that concrete compressive strength is not affected significantly by the inclusion of fiber. Thus, it can be concluded that fibers have little effect on the compressive strength. However, the use of fibers substantially increased the post-cracking ductility and hence energy absorption of the material. This result is consistent with the findings of earlier research.

The effect of fiber on flexural tensile strength and ductility is given in Fig. 2. It is observed that although the flexural tensile strength of fiber reinforced concrete is on average only slightly higher than the strength of regular concrete with similar compressive strength, but the ductility of fiber reinforced concrete is significantly larger than the regular concrete. It should be noted that regular concrete did not exhibit any post-peak behavior on their flexural behavior. However, the fiber reinforced concrete exhibited a stable post-peak behavior with a very good ductility.