- Technical Paper -

SHEAR BEHAVIOR OF REINFORCED CONCRETE BEAMS USING HIGH-STRENGTH CONCRETE

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ABSTRACT

In this research, eleven reinforced concrete (RC) beams using high strength concrete (HSC) were tested to clarify the shear strength and failure mechanism. The experimental variables include compressive strength of concrete (40, 100, 160MPa) and shear span to depth ratio (a/d=3, 3.5, 4). According to JSCE code, the shear strength of RC beam increases as the concrete strength increases. However, the experimental results showed that, the shear strength of RC beam using HSC did not increase. In addition, as compared to normal strength concrete (NSC) specimen, the transition point of HSC specimen (on a/d ratio) from the arch action into beam action shifted to a higher value.

Keywords: beam, high strength concrete, reinforced concrete, shear failure, shear strength

1. INTRODUCTION

High-strength concrete has recently been adopted in buildings in most cases but has only been applied to bridge structures in a few instances [1]. Adopting high-strength concrete for bridge structures enables the use of lighter members, reduction in seismic force, use of longer spans, reduction in girder height and improved durability. Therefore, high value-added or high performance structures that cannot be realized with ordinary concrete can be constructed. Thus, applying high-strength concrete to bridge structures provides numerous benefits. Furthermore, high-strength concrete will be more and more frequently used in columns, precast elements and structures where member size and durability are important design parameters [2].

However, an increase in the concrete strength produces an increase in its brittleness and smoothness of shear failure surfaces, leading to some concerns about the application of high strength concrete. Recently, most of the current shear procedures based on tests were carried out on beams with a concrete compressive strength lower than 80 MPa. Till now, very few studies have been conducted on shear behavior of RC beams with concrete strength of range between 100 to 160 MPa [3]. In addition, the mechanism of shear failure is not fully understanding because of the lack of research in high-strength concrete beams with different shear span to depth ratios (a/d ratios) [4]. Therefore, the transition point of shear failure mechanism is not clearly found with a/d ratio.

Based on this background, the objectives of this study are to explore the shear strength and the failure mechanism of high-strength concrete. In this study, an experimental program was conducted. The variable parameters include the compressive strength of concrete and shear span to depth ratio. According to JSCE design equation [5], the shear strength of RC beam increases as the concrete strength increases. However, in case of high-strength concrete, the experimental results showed that with the increase of concrete strength, the shear strength of RC beam did not reach to a higher value. In addition, as comparing to normal strength concrete specimen, the transition point of high-strength concrete specimen (on a/d ratio) from the arch action into beam action shifted to a higher value.

2. EXPERIMENTAL PROGRAM

2.1 Details of specimens and test variables

In order to investigate the influence of compressive strength of concrete and a/d ratio on shear behavior of HSC beams, an experimental program was carried out. Eleven identical beams with rectangular section were used in this study. Test specimens consisted of nine RC beams without web reinforcement (S series) and two RC beams with web reinforcement (SS series). The cross sections and layout of test beams are shown in Fig. 1 and Fig. 2, respectively. Three high strength steel bars (f_y = 750 MPa) were laid at the bottom of the section so as to precede the shear failure than flexural failure. The test variables were compressive strength of concrete (target strength of 40, 100, 160 MPa) and a/d ratio (a/d = 3, 3.5, 4).

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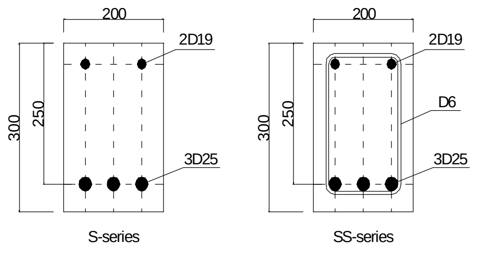


Fig.1 Cross section (mm)

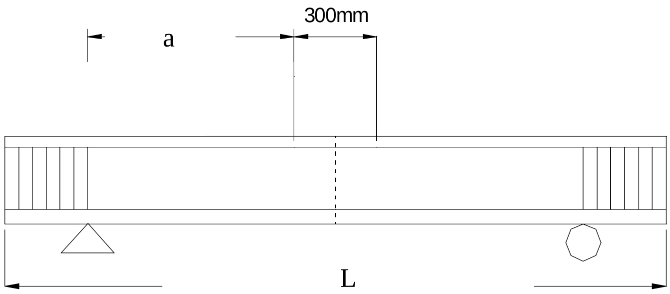


Fig. 2 Layout of test beams

Table 1 Concrete mix proportion

Type	Cement	W/C (%)	Unit Weight (kg/m^3)					
			W	C	G	S	SP*	DA*
40 MPa	OPC	46	168	363	757	1017	3.45	—
100 MPa	OPC	23	165	717	940	608	12.9	0.78
160 MPa	SFC	17	155	912	795	615	14.6	0.9

Table 2 Properties of steels

Type		f_y (MPa)	E x 10^3 (MPa)
Steel	D6	360	187
	D19	384	200
	D25	750	201

* OPC: Ordinary Portland cement, SFC: Silica fume cement
SP: Super-plasticizer (C*%), DA: Air reducing admixture (C*%).

Table 3 Test variables

Number	Type	f'_c (MPa)	a/d	Stirrup Spacing (mm)
1	S-40-1-3.0	40	3	-
2	S-100-1-3.0	100	3	-
3	S-160-1-3.0	160	3	-
4	S-40-2-3.5	40	3.5	-
5	S-100-2-3.5	100	3.5	-
6	S-160-2-3.5	160	3.5	-
7	S-40-3-4.0	40	4	-
8	S-100-3-4.0	100	4	-
9	S-160-3-4.0	160	4	-
10	SS-40-1-3.0	40	3	125 (P_w=0.253 %)
11	SS-160-1-3.0	160	3	

The concrete mix proportions are tabulated in Table 1. The binding material was low-heat Portland cement with 10% (by cement mass) replacement of silica fume powder. The mechanical properties of steels used in the experiment are listed in Table 2. The test variables are summarized in Table 3.

2.2 Instrumentation and test procedures

The four point symmetrical loading with distance of 300 mm between the loading points was statically applied to all of specimens (Fig.2). All cracks that developed during the loading were observed and marked in details. Crack patterns of beams were redrawn in computer. Based on the crack pattern, the direction of the crack opening and the location of the crack were determined.

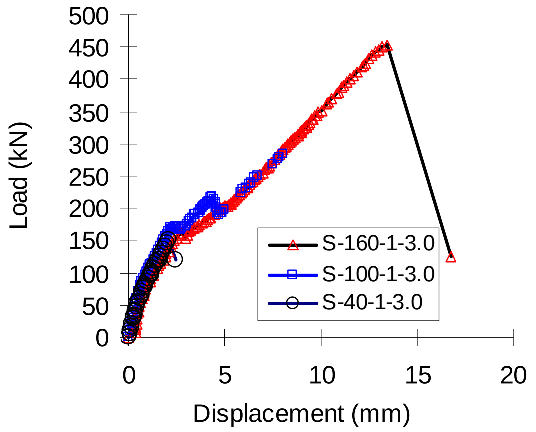
3. TEST RESULTS AND DISCUSSION

3.1 Shear force and deformation relationship

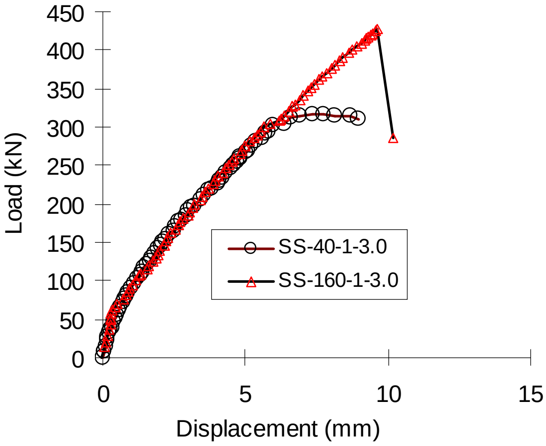
In order to investigate the relationship between shear force and deformation of RC beams, the experiment was tested with two different series including SS series (with shear reinforcement) and S series (without shear reinforcement). In case of SS series, concrete with the compressive strength of 40 MPa and 160MPa were used. To clarify the shear strength of beams without shear reinforcement, compressive strength of concrete was 40 MPa, 100 MPa, and 160 MPa.

Fig. 4 shows the relationship between load and displacement (with a/d = 3.0) for different compressive strength of concrete. As expected at a/d ratio of 3.0, failure load increases with compressive strength of concrete for both beams with and without shear reinforcement. In the case that a/d ratio is 3.0, HSC beams failed in shear compression and NSC beams failed in diagonal tension.

Fig. 5 shows the relationship of shear force and the deformation of the RC beams in case a/d ratio is 4.0. In this case, the shear strength of RC beams did not increase with the increase in concrete strength. In the case that a/d ratio is 4.0, both NSC and HSC specimens failed in diagonal tension. The same result can also be observed in the paper done by Bentz [6].



a) Without shear reinforcement



b) With shear reinforcement

Fig.4 Shear force and deformation relationship (a/d = 3.0)

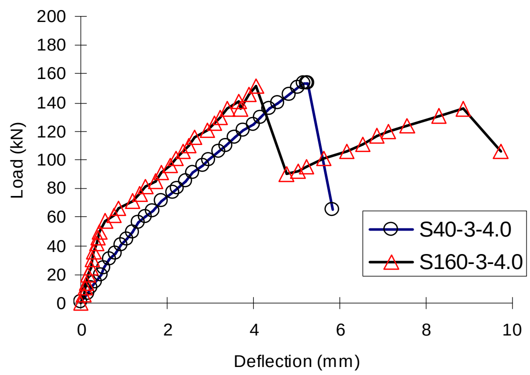


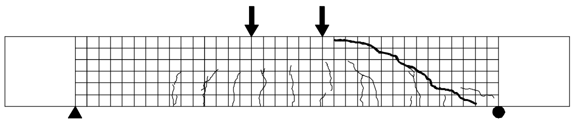
Fig.5 Shear force and deformation relationship (a/d=4.0)

3.2 Failure mode and crack pattern

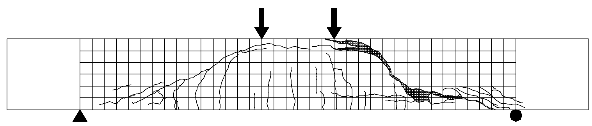
Crack patterns at failure for both NSC and HSC specimens are shown in Fig. 6. All specimens failed in shear failure mode. The failure loads and failure mode are presented in Table 4. The failure of HSC specimens showed brittle behavior compared to NSC specimens (Fig. 7a, b). The higher their concrete compressive strength, the brisker their failure. HSC beams with stirrups presented a less fragile response than similar beams without web reinforcement (Fig. 7c). Experimental results stated that at a/d ratio of 3.0, the failure mode of NSC beams followed diagonal tension while HSC beams failed in shear compression. For NSC, failure mode changes from arch action to beam action at a/d ratio of around 3.0. However, the failure mode of HSC beam was shear compression even a/d ratio of 3.5 (Table. 4). The change of mechanism of shear failure mode in HSC will be discussed further in the part 4.3.

Table 4 Failure loads

Type	Shear Cracking Load	Failure Load	Failure Mode
	(kN)	(kN)	
S-40-1-3.0	150	150	Diagonal Tension
S-40-2-3.5	156	156	Diagonal Tension
S-40-3-4.0	153	153	Diagonal Tension
S-100-1-3.0	171	284	Shear Compression
S-100-2-3.5	170	186	Shear Compression
S-100-3-4.0	170	170	Diagonal Tension
S-160-1-3.0	203	452	Shear Compression
S-160-2-3.5	154	160	Shear Compression
S-160-3-4.0	151	151	Diagonal Tension
SS-40-1-3.0	106	316	Shear Compression
SS-160-1-3.0	125	426	Shear Compression



a) S-40-1-3.0



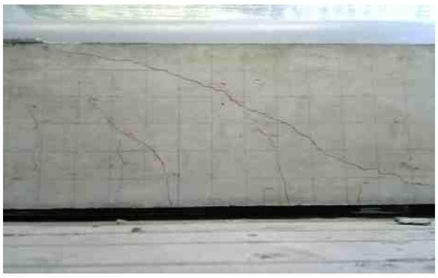
b) S-160-1-3.0

Fig.6 Shear failure pattern of NSC and HSC beams

3.3 The length of diagonal tension crack

Fig. 8 shows the length of a diagonal tension crack in the compression zone obtained from experimental results. The length of a diagonal tension crack, which is required to penetrate the compression zone, can be calculated as $x=c/\tan\theta c$, where c equals the depth of the compression zone, and θc equals the angle of an inclined tension crack in the compression zone that is defined as the principal tensile stress axis [8].

According to Fig. 8, in case of HSC beam (S-100-1-3.0), the length of diagonal tension was shorter than in case of NSC beam (S-40-1-3.0) even at same a/d ratio. In the other words, θc values of HSC specimens were higher than those of NSC.

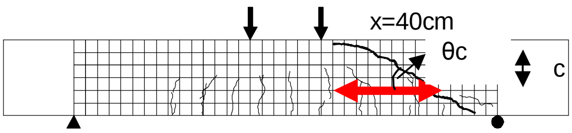


a) S-40-1-3.0

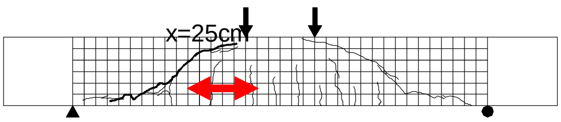
b) S-160-1-3.0

c) SS-160-1-3.0

Fig.7 Failure mode of NSC and HSC beams



(a) Specimen S-40-1-3.0



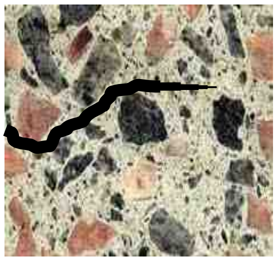
(b) Specimen S-100-1-3.0

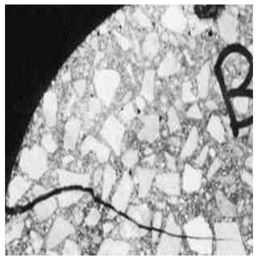
Fig.8 The length of diagonal tension crack (x)

4. NUMERICAL SIMULATION

4.1 Numerical method

The numerical simulation was carried out using Modified Compression Field Theory (MCFT). Experimental variables and actual compressive strength of concrete of the test specimens were used in the numerical model. The numerical simulation in the model combines a plane section analysis for flexure with the modified compression field theory for shear that accounts for strain compatibility and uses the tensile and compressive stress-strain relationships for diagonally cracked concrete [7]. In addition, constitutional models for concrete and other material were used as described in the numerical program. The material properties of concrete and steel used in the numerical model were based on the experimentally measured values and details provided by manufactures (see Tables 1 and 2). In HSC, the crack surfaces were observed to be relatively smooth (Fig. 9b), because cracks penetrated through aggregates. This phenomenon reduces the aggregate interlock and shear strength of the beams. MCFT allows simulating this smooth crack by reducing the aggregate size from the real value down to 0 when the compressive strength of concrete is over 80MPa.





a) Normal strength concrete b) High strength concrete

Fig.9 Crack pattern through the concrete

In this paper, the comparison of two modeling method using MCFT and 2D-FEM was carried out. A 2D-FEM method was used to predict the shear behavior of the specimens. In 2D-FEM, a smeared crack model based on average stress-average strain was used to model concrete after cracking. For post cracking behavior compression and tension model proposed by Maekawa et al. [8], were used. For reinforcement, nonlinear path dependent constitutive model proposed by Fukuura and Maekawa was used. In 2D-FEM, to describe the geometry of the crack plane simply, the crack shear transfer magnification factor was used.

4.2 Comparison of load – deflection relationship

Fig. 10 shows the comparison of load and mid span deflection relationship between the experimental data and numerical analysis results for HSC beam (S-160-3-4.0) using MCFT. In addition, the 2D-FEM was used to estimate this relationship of specimen HSC beam (S-100-3-3.0) as shown in Fig. 11. The prediction of the shear strength using MCFT generally shows good agreement with the experimental results in the case that the RC beam failed in diagonal tension mode.

However, the predicted value is about 15% higher than the experimental failure load. The reason might be due to the program did not verify with higher concrete strength as 160MPa. The analysis results presented in Fig. 11 confirmed that 2D-FEM can well predict not only the shear strength but also the failure mode.

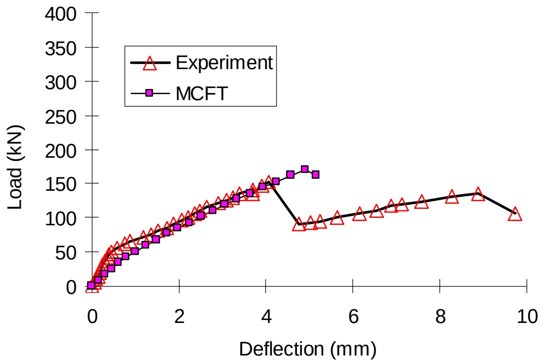


Fig. 10 Numerical simulation for specimen S-160-3-4.0 (using MCFT)

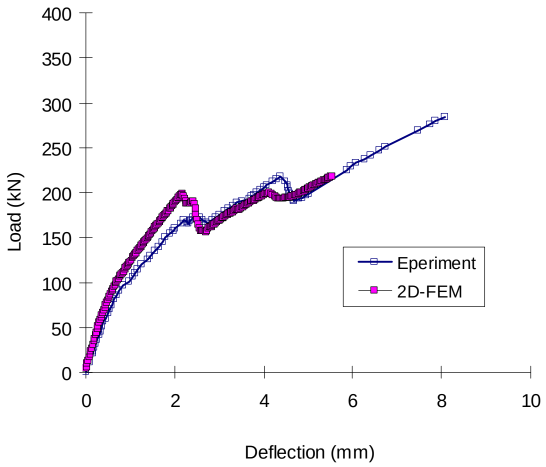


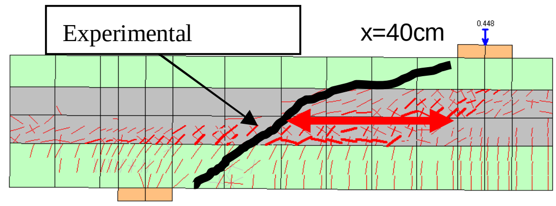
Fig. 11 Numerical simulation for specimen S-100-1-3.0 (using 2D-FEM)

4.3. The change of mechanism of shear failure mode in HSC

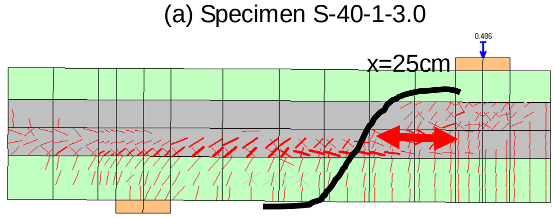
From the experimental results in section 3.2, it was found that as comparing to NSC, the transition point of HSC (on a/d ratio) of the arch action into beam action shifted to a higher value (the transition point occurred at a/d ratio of 3.0 and 4.0 for NSC and HSC, respectively.)

Fig. 12 introduced the crack pattern of specimens at two different compressive strength (40MPa, and 100MPa) simulated by using 2D-FEM. From this figure, it can be concluded that 2D-FEM can be used for predicting the shape of critical crack.

Experimentally, the higher value of compressive strength, the bigger θc. θc values were about 45 degree and 54 degree in case of NSC beam (S-40-1-3.0) and HSC beam (S-100-1-3.0), respectively. In addition, the length of a diagonal tension crack x=c/tanθc was inversely proportional to θc. It means that the higher the compressive strength, the smaller x value was obtained. The analysis result showed that x decreased from 40cm to 25cm when the compressive strength of changed from 40 MPa to 160 MPa. Theoretically, the formation of arch action will be occurred just only when the length of diagonal tension crack approximates to the effective depth of the beam (d) [9]. With HSC beam (S-100-1-3.0), x value is equal to d value. It means that arch action will be formed and failure mode is shear compression. This phenomenon observed in Fig.8 well agreed with the numerical analysis as shown in Fig.12.



(a) Specimen S-40-1-3.0



(b) Specimen S-100-1-3.0

Fig. 12 Crack pattern simulated by using 2D-FEM

The analysis results show that MCFT can accurately predict shear capacity when a/d ratio is higher than 2.5 [6]. In addition, 2D FEM well predicts shear capacity even at low a/d ratio, but 2D FEM limited to 100MPa concrete strength [8]. Therefore both these methods were use to verify experimental results with HSC and low a/d ratio. According to numerical analysis, the transition points of NSC beam and HSC beam will be occurred at a/d ratio of 3 and 4, respectively. The numerical analysis agrees with the experimental results in the case of transition point of shear failure mechanism (Fig. 13).

Because of the decreasing of the length of diagonal tension crack, aggregate interlocking is smaller in HSC beams as compared to NSC beams. In case of shear compression failure, shear strength of RC beams is assumed to be resisted mainly by the compression of uncracked concrete part rather than by the tension zone. However, in case of diagonal tension failure, shear strength of RC beams strongly depended on aggregate interlocking. In HSC, the observed crack surfaces were relatively smooth, because cracks penetrated through aggregates. This phenomenon made the aggregate interlock reduction.

In order to increase the shear capacity of HSC beams, one valuable suggestion is to introduce aggregates with high stiffness. According to numerical analysis, it is possible to increase shear capacity of HSC beam, but it should be experimentally verified (Fig.14). During the numerical analysis using 2D-FEM the "crack shear transfer magnification factor (α)" increased from 0.2 to 1.0 ("α" is equal to 1.0 for NSC).

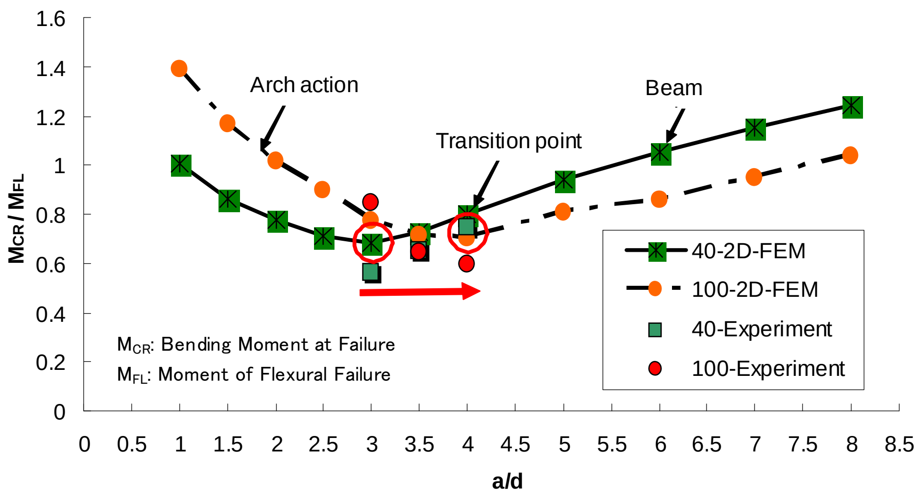


Fig. 13 The change of transition point of shear failure mechanism [10]

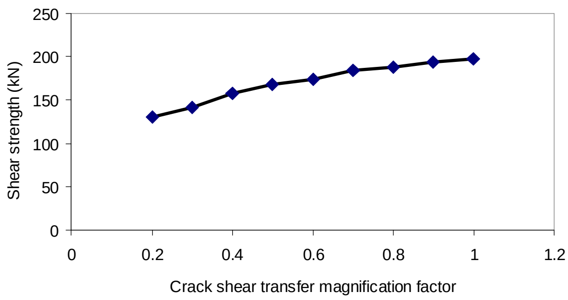


Fig. 14 Influence of crack shear transfer magnification factor (2D-FEM)

5. CONCLUSIONS

This study presents the results of an experimental investigation on shear behavior of RC beams using high-strength concrete. The following conclusions can be drawn:

(1) High-strength concrete beams without web reinforcement show a very brittle behavior. The higher their concrete compressive strength, the brisker their failure. High-strength concrete beams with stirrups present a less fragile response than similar beams without web reinforcement.

(2) With the increase of concrete strength, the shear strength of high-strength concrete beams without web reinforcement does not reach to a higher value. For beams with web reinforcement, the shear strength increases as the concrete strength increases.

(3) As compared to normal strength concrete beam, the transition point of high-strength concrete beam (on a/d ratio) from the arch action into beam action shift to a higher value. For 160MPa concrete strength, the transition point is about 4.0.

(4) The MCFT can well predict the shear capacity of RC using high-strength concrete.

(5) Numerical study shows that aggregate with higher stiffness can increase the shear capacity of high-strength concrete beams but it should be experimentally verified.

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