Effects of high loading rate on reinforced concrete beams

Fujikake, Kazunori; Adhikary, Satadru Das; Li, Bing

2014

Adhikary, S. D., Li, B., & Fujikake, K. (2014). Effects of High Loading Rate on Reinforced Concrete Beams. *ACI Structural Journal*, 111(3), 651-660.

<https://hdl.handle.net/10356/104860>

© 2014 American Concrete Institute. This paper was published in *ACI Structural Journal* and is made available as an electronic reprint (preprint) with permission of American Concrete Institute. The paper can be found at the following official URL:
<http://www.concrete.org/Publications/ACIMaterialsJournal/ACIJJournalSearch.aspx?m=details&ID=51686579>.
One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 07:20:10 SGT

Title No. 111-S54

Effects of High Loading Rate on Reinforced Concrete Beams

by Satadru Das Adhikary, Bing Li, and Kazunori Fujikake

The majority of past research on reinforced concrete (RC) beams has focused on their behavior under static and relatively slow loading rates, while limited attention has been paid to the corresponding behavior under high loading rates. Thus, a comprehensive literature review has been conducted on RC beams under varying loading rates to observe the overall trend of dynamic increase factor (DIF) of maximum resistance and failure modes. The wide range of data pertaining to DIF and the apparent changes in failure modes means, however, that general agreement has yet to be reached among researchers. To supplement the limited literature in this field, 24 RC beams were tested under four different loading rates ranging from slow (4×10^{-4} m/s) to fast (2 m/s) to cover the wide range of loading scenarios (quasi-static, earthquakes, and impact regime). Comparative analyses of RC beams under these varying loading rates highlighted several key aspects of their dynamic behavior.

Keywords: beam; dynamic behavior; dynamic increase factor; loading rate; reinforced concrete.

INTRODUCTION

Over the past few decades, there has been a growing interest among researchers and designers in analyzing and designing RC structures against extreme loads, such as earthquakes, blasts, and impact. These loading scenarios induce varying strain rates in the structural elements, as shown in Fig. 1. In this study, the strain-rate effect on RC beams falls in the wider range (enclosed by an ellipse in Fig. 1) of static to hard impact (10^{-4} to 10/s) regime. A variety of devices, such as hydraulic machines, pneumatic machines, and impact systems (mass swings or falls from specific heights to strike a specimen), have been constructed to perform high loading rate tests on structural elements in the laboratory.¹⁻³ Previous studies^{4,5} on high loading rates of RC beams were confined up to the earthquake loading regime. Fujikake et al.⁶ considered a much higher piston velocity for high loading rates that could be linked to the impact loading regime; however, it considered only one test parameter (that is, the flexural reinforcement ratio). There is a lack of systematic research on RC beams under a wide range of varying loading rates to cover static loading to hard impact regime. Therefore, a well-instrumented experimental program was initiated to investigate the effects of varying loading rates on the structural behavior of RC beams with a limited amount of flexural reinforcement (approximately $0.3p_b$, where p_b refers to balanced reinforcement ratio in percentage). In this study, a hydraulic machine was used to generate the wide range of loading rates extending from 4×10^{-4} to 2×10^0 m/s (1.3×10^{-3} to 6.6×10^0 ft/s). The corresponding strain rate induced in the reinforcements of

Fig. 1—Spectrum of strain rate.⁴

RC beams ranged from 10^{-4} /s to 10/s. This paper documents the details of previous research in this area, and the current test program, including specimen characteristics, material properties, test setup, instrumentations, and test procedure. Test results and major observations are comprehensively presented and discussed.

RESEARCH SIGNIFICANCE

Review of literature related to the performance of RC beams under varying loading rates reveals a paucity of works addressing the behavior of beams under a wide range of varying loading rates. The primary objective of this research is to study the effect of loading rate on the load-versus-midspan displacement relationships, concrete contribution to the shear stress, and peak strain rate at longitudinal tensile and shear reinforcements. Moreover, the dynamic increase factor (DIF), cracking stiffness, energy absorption, and failure mechanism of beams are also discussed by comparative analysis. In addition, this test program will supplement the literature with detailed test data that can assist in the further development and verification of analytical and numerical studies.

EXPERIMENTAL DATABASE OF REINFORCED CONCRETE BEAMS UNDER VARYING LOADING RATES

Rate effects at the constitutive level of structural material⁷⁻¹⁰ have been well documented in literature; however, investigation into the structural behavior under varying loading rates is very limited. Mutsuyoshi and Machida⁴ tested 27 singly and doubly reinforced beams under different loading rates, noting that the final mode of failure shifted from flexure at a low rate to shear at high loading rate for two pairs of specimens having shear span-effective depth ratio (a/d) = 4 and 5.7, where a is the shear span, and d is the effective depth of the beams. Seven pairs of singly reinforced beams were

ACI Structural Journal, V. 111, No. 3, May-June 2014.

MS No. S-2012-289.R1, doi: 10.14359/51686579, was received March 4, 2013, and reviewed under Institute publication policies. Copyright © 2014, American Concrete Institute. All rights reserved, including the making of copies unless permission is obtained from the copyright proprietors. Pertinent discussion including author's closure, if any, will be published ten months from this journal's date if the discussion is received within four months of the paper's print publication.

tested by Kulkarni and Shah.⁵ For each pair, one beam was tested at a static rate (7.1×10^{-6} m/s [2.3×10^{-5} ft/s]), while the other was tested at a high rate (3.8×10^{-1} m/s [1.25 ft/s]). In this study, the strain rates generated in the reinforcements of beams by high loading rates can be correlated to the earthquake-induced strain rates. For the three pairs of beams ($a/d = 4, 4.5$, and 5) tested,⁵ however, an opposite phenomenon (that is, transition in the mode of failure from shear failure at the static rate to flexure failure at the high loading rate) has been observed. It was concluded that the difference in the observed failure tendencies in these studies might be attributed to the strain rate effect on the yield strength of steel used in the two studies. Furthermore, Fujikake et al.⁶ performed the testing of three pairs of doubly reinforced concrete beams with varying amounts of longitudinal reinforcements, but the shear reinforcement ratios were kept identical for all specimens. For each pair, one beam was tested at a static rate (5×10^{-4} m/s [1.6×10^{-3} ft/s]) while the other was tested at a high rate (2 m/s [6.6 ft/s]). As compared with Kulkarni and Shah,⁵ Fujikake et al.⁶ considered a much higher piston velocity for high loading rates, which could be linked to the impact loading regime. All specimens failed in flexure under both static and high loading rates. The ultimate resistance of the beams was enhanced by the increment of longitudinal tensile reinforcements for both static and high loading rates. Thereafter, Adhikary et al.^{11,12} and Fujikake et al.¹³ investigated the behavior of 48 RC beams under varying rates of concentrated loading (static, low, medium, and high) in which the shear span-effective depth ratio ($a/d = 3.3$ and 1.9) and shear reinforcement ratio were the key variables. Shear-critical RC beams of the 3.3 series exhibited more catastrophic failure modes (different types of shear failure) for loading rates higher than static loading, including the fragmentation of beams into several pieces, exposure and bending of longitudinal reinforcements, and massive cracking and spalling of concrete. On the other hand, flexure-critical beams of the same series had a much milder response in failure mode under loading rates higher than static loading. Shear compression or diagonal splitting-type failure, or both, was observed in all short beams ($a/d = 1.9$), irrespective of applied loading rates at their midspan. Much ductile behavior, however, was perceived when the specimens contained a higher amount of shear reinforcement (0.84%). Maximum resistance of the RC beams improves with an increase in loading rate. The influence of loading rates on the maximum resistance is more significant for the shear-failure type beam than those that failed in flexure. The smaller the shear reinforcement ratio and a/d , the greater the influence of loading rates on the shear resistance of beams. Furthermore, it was observed that peak strain rates of longitudinal tensile reinforcements were amplified by one order of magnitude (approximately 10 times) as the loading rates were increased from low to high.

A database of RC beams under different loading rates has been assembled from the literature to conduct the parametric studies with an objective of gaining some insight on the influence of several parameters (a/d , longitudinal reinforcing bar ratios p_L , shear reinforcing bar ratios p_s , and failure modes) on the DIF of maximum resistance. The data-

Fig. 2—Influence of: (a) shear span-effective depth ratio (a/d); (b) longitudinal reinforcing bar ratios p_L ; and (c) failure mode on DIF of singly reinforced beams. (Note: 1 m/s = 3.28 ft/s.)

base containing the particulars of the specimens is tabulated in the Appendix.*

Most of the RC beams shown in the Appendix can be classified into singly reinforced concrete beams without shear reinforcement (SR), and doubly reinforced concrete beams with shear reinforcement (DR). Thus, a parametric study has been carried out for SR and DR beams separately to determine the effect of several parameters on their corresponding DIF of maximum resistance. Figure 2(a) shows the influence of a/d on the trend of variation of DIF of SR beams. Effects of longitudinal reinforcing bar ratios and failure mode on DIF under different loading rates are shown in Fig. 2(b) and (c). Due to scattering of data points, it is very tough to ascertain the effects of single parameters on DIF of SR beams. Failure modes (shear or flexure) and the time of yielding of tensile reinforcements (before or after the peak resistance of shear critical beams) have some significant effect on DIF. In Fig. 2(c) for 0.1 to 1 m/s [0.328 to 3.28 ft/s] few DIFs are higher than the clustering data points. In these cases, yielding of tensile reinforcing bars occurred after their peak resistance. Similarly, influence of a/d , p_L , and p_s and failure mode on DIF of DR beams are shown in Fig. 3(a), (b), (c), and (d), respectively. From the trend of DIFs, it can be concluded that beams with a lower a/d (1.9) have more DIFs under varying loading rates as compared with slender beams ($a/d = 3.3$ and 4.4). Beams of low shear reinforcement had a higher DIF value compared with other specimens. When the specimen contains less shear reinforcements, it may fail in shear, where the tensile strength of concrete (more rate-sensitive than compressive strength) plays a significant role in increasing the ultimate resistance under high loading rates and correspondingly increases the DIF. Finally, based on

*The Appendix is available at www.concrete.org/publications in PDF format, appended to the online version of the published paper. It is also available in hard copy from ACI headquarters for a fee equal to the cost of reproduction plus handling at the time of the request.

Fig. 3—Influence of: (a) shear span-effective depth ratio (a/d); (b) longitudinal reinforcing bar ratios p_L ; (c) shear reinforcing bar ratios p_s ; and (d) failure mode on DIF of doubly reinforced beams. (Note: $1 \text{ m/s} = 3.28 \text{ ft/s}$.)

the comparative plot of DIF versus failure modes, it can be concluded that shear critical beams produced higher DIFs as compared with flexure critical for all loading rates.

The review of existing literature revealed a variety of high loading rate tests with numerous parameters, which renders effective comparisons more difficult. As such, it will be beneficial if researchers can agree on a preferred way to perform high-loading-rate testing of RC beams. There are some major differences in the testing methods worth noting. At first, the test setup may be designed for three- or four-point bending depending on the objective of the test program. For high-loading-rate testing using hydraulic machines, three-point configurations were recommended by Kulkarni and Shah⁵ from the point of view of reducing inertial effects. Furthermore, it was realized by the current authors that an attempt should be made to test identical specimens (that is, similarities not only in the structural level, but also in the material level, such as aggregate size, compressive strength of concrete, and yield strength of reinforcements) using different test machines. Time to reach peak displacement in loading history (for a particular loading rate in displacement control) should be kept nearly unvarying. The data acquisition system (particularly frequency response characteristics) should be nearly identical to facilitate better analysis and comparisons. In addition, the type of anchorage (that is, by nuts, welded with plates or development length by hooking) at the end of flexural reinforcements has a profound effect on the shear failure mechanism of beams (which will be governed by arch or beam action) under varying loading rates, and should as such be kept identical across the tests.

EXPERIMENTAL INVESTIGATION

To date, limited research has been performed to explore the behavior of RC beams under a wide range of loading rates. Meticulous inspection of the database provided in the Appendix reveals that the behavior of RC beams with

Fig. 4—Flow chart of test program.

intermediate slenderness under varying loading rates is still deficient. With an intention of contributing to that scarce research area, an experimental program was undertaken for RC beams with a limited amount of flexural reinforcements ($0.31p_b$ and $0.3p_b$ for 3.3 and 4.4 series, respectively, where p_b refers to balanced reinforcement ratio in percentage) subjected to a wide range of loading rates (static: 4×10^{-4} , low: 4×10^{-2} , medium: 4×10^{-1} , and high: $2 \times 10^0 \text{ m/s}$ [static: 1.3×10^{-3} , low: 13.2×10^{-2} , medium: 4×10^0 , and high: $6.6 \times 10^0 \text{ ft/s}$]). Comparative analyses of specimens under these varying loading rates highlighted several key aspects of their dynamic behavior.

The experimental program consisted of 24 RC beams which were divided into two groups in terms of their a/d . Each group had three types of specimens distinguished by their shear reinforcement ratio. The entire test program was epitomized in the form of a flow chart, as shown in Fig. 4. The specimen denoted by SR3.3_0.84 corresponds to a singly reinforced beam (SR) followed by the a/d and percentage of longitudinal tensile reinforcement ratios. Again, DR3.3_0.84_0.11 refers to a doubly reinforced beam (DR) followed by the a/d , percentage of longitudinal tensile and compressive reinforcement ratio, and percentage of shear reinforcement ratio. Each type had four identical specimens subjected to four types of varying rates of concentrated loading at their midspan. The layout of the longitudinal reinforcements, spacing of shear reinforcements, and the measuring points (acceleration and strain for steel reinforcing bars) are shown in Fig. 5. Longitudinal reinforcements consisted of deformed steel bars of T13 (diameter of 13 mm [0.5 in.]) and T10 (diameter of 10 mm [0.39 in.]) for $a/d = 3.3$ and 4.4 series specimens, respectively, while R6 (diameter of 6 mm [0.23 in.]) plain round bars were used as shear reinforcements for all specimens. The target concrete compressive strength at 28 days was 40 MPa (5.8 ksi), with a maximum aggregate size of 10 mm (0.4 in.) for all specimens. The yield strengths of T13, T10, and R6 were 520, 510, and 310 MPa (75.4, 73.9, and 44.9 ksi), respectively.

Table 1—Specimen details, theoretical static capacities, static expected, and observed failure mode

Specimens	a/d	Longitudinal reinforcing bar ratio, %	Shear reinforcing bar ratio, %	Flexural resistance, kN (kip)	Shear resistance, kN (kip)	Shear to bending resistance ratio	Expected failure mode	Observed failure mode
SR3.3_0.84	3.3	0.84 ^T	0	77.1 (17.3)	66.2 (14.9)	0.86	Shear	Shear1*
DR3.3_0.84_0.11		0.84 ^{T and C}	0.11	77.6 (17.4)	87.1 (19.6)	1.12	Flexure	Shear2†
DR3.3_0.84_0.15		0.84 ^{T and C}	0.15	77.6 (17.4)	95.5 (21.5)	1.23	Flexure	Shear1*
SR4.4_0.82	4.4	0.82 ^T	0	33.7 (7.6)	40.2 (9.0)	1.19	Flexure	Flexure
DR4.4_0.82_0.13		0.82 ^{T and C}	0.13	34 (7.6)	56.1 (12.6)	1.65	Flexure	Flexure
DR4.4_0.82_0.19		0.82 ^{T and C}	0.19	34 (7.6)	62.5 (14.0)	1.83	Flexure	Flexure

*Shear1 is shear failure following yielding tensile reinforcements.

†Shear2 is shear failure following flexure compression failure.

Notes: T is only tensile reinforcing bars; T and C are tensile and compressive reinforcing bars.

Fig. 5—Dimensions of RC beams, layout of reinforcements, and location of strain gauges and accelerometers. (Note: 1 mm = 0.04 in.)

All specimens were cast at the same time using ready mixed concrete of same the batch; hence, all specimens had an identical concrete strength. The compressive strength at 28 days obtained from three concrete cylinders was 39.0, 39.6, and 42.2 MPa (5.70, 5.74, and 6.10 ksi), respectively. The specimen details, theoretical static capacities, static expected, and observed failure modes are listed in Table 1, where the static flexural and shear resistances are calculated according to ACI 318-08.¹⁴ According to this table, except SR3.3_0.84, all specimens are theoretically flexure-dominant (shear-bending resistance ratio is greater than one) under monotonically increasing static loads. For the DR3.3 series, however, shear failure mode was observed under static loading. The reason for inconsistency between the expected and observed failure modes in DR3.3 specimens is the wider interval of the stirrups. ACI 318-08¹⁴ sets the maximum spacing of vertical stirrups as the smaller of $d/2$ or 610 mm (24 in.). Following ACI code, the vertical stirrups surely intersect at a diagonal shear crack formed in the RC beam. Thus, stirrups were not

effective at all in preventing shear failure. All specimens were well instrumented to capture the loads, displacements, accelerations, and strains of the steel reinforcing bar. The instrumentation for this test program included a load cell, strain gauges, and accelerometers. A load cell of capacity of 980 kN (220.3 kip) and measuring frequency of 5 kHz was attached to the actuator to measure the load. Strain gauges were installed in the midspan of the longitudinal tensile reinforcements and in the midpoint of the two legs of the shear reinforcements. Five accelerometers (capacity of 1000 times gravity and resonance frequency of more than 70 kHz) were mounted on the specimens for each test (except for static loading) to measure the accelerations for low, medium, and high rates of concentrated loading. The midspan deflection of RC beams was measured by laser-type variable displacement transducers (LVDTs), which have a measuring range of 80 mm (3.2 in.) and sampling rate of 50 kHz. Data from the sensors were collected by a digital data acquisition system, which had a sampling rate of 100 Hz, 10 kHz, 100 kHz, and

Fig. 6—Schematic diagram of test setup.

200 kHz for static, low, medium, and high loading rates, respectively. A steel plate with a 40 mm (1.6 in.) thickness was placed on top of the beam in between the loading bar and specimen to transfer well-distributed force to the specimen. The use of digital photography and high-speed video recording proved to be valuable in providing insights into the cracking patterns and failure modes. A schematic diagram of the three-point bending test setup is shown in Fig. 6.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Load-midspan displacement relationship

The input load by the actuator was measured by the load cell attached, and the reaction forces were measured by two load cells placed at the two pin supports of the beams. For static, low, and medium loading rates, almost identical responses (that is, load-midspan deflection) were obtained from the top and two bottom load cells. For high loading rates, however, higher response was obtained from the two bottom load cells as compared with the top load cell. The 100 kg (220 lb) mass of each supporting apparatus attached to each support load cell might induce additional responses. The wider range of frequency of the load acting on the lower load cells compared with its natural frequency could be another reason for the higher response. Thus, the reaction force (summation of two bottom load cells) obtained from high loading rates might overestimate the true resistance of the beam. Hence, inertia force was deducted from the top load cell data (that is, using the following equation) by considering the beam as a SDOF system to evaluate its true resistance.

$$R_b(t) = P_{TL}(t) - M_b \times \ddot{x}_b(t) \quad (1)$$

where $R_b(t)$ is the true resistance of the RC beam without inertia force; $P_{TL}(t)$ is the load measured by top load-cell; M_b is the equivalent mass of the RC beam (that is, $17rAL/35$; r is the density of the RC beam; A is the sectional area of the beam; L is the span length in between supports); and $\ddot{x}_b(t)$ is the acceleration at midspan obtained from accelerometers. Another 25 kg (55 lb) of extra mass (considering the mass

Fig. 7—Load versus midspan deflection of: (a) $a/d = 3.3$; and (b) $a/d = 4.4$ series specimens under varying loading rates.

of the loading bar) was added to the equivalent mass of the beam to calculate true resistance.

The comparisons of the load-midspan displacement relationship of each specimen to the corresponding loading rates are illustrated in Fig. 7. Due to an unforeseen problem, the response of the beam named DR4.4_0.82_0.19 under low loading rates could not be captured; hence, the corresponding beam response has been omitted. The load-carrying capacity of all specimens increases with incremental loading rates. DIFs of $a/d = 3.3$ and 4.4 series specimens are shown in Fig. 8(a) and (b), respectively. From the comparative analysis of the aforementioned two figures, DIF for the 3.3 series seems to be higher than the 4.4 series due to their contrasting nature of failure mode. It is noteworthy that DR beams had less DIF as compared with SR; however, for DR3.3_0.84_0.15, resistance for the low loading rate has been used to calculate DIF. As there is no sign of ductile behavior with strain hardening (that is, sudden

Fig. 8—Dynamic increase factor (DIF) of maximum resistance of: (a) $a/d = 3.3$; and (b) $a/d = 4.4$ series specimens under varying loading rates.

Fig. 9—Concrete contribution to shear stress.

drop in load-deformation curves after peak load, although the longitudinal tensile reinforcing bars yielded before the beam attained peak resistance) in the load-versus-midspan deflection curves of DR3.3_0.84_0.15, the peak resistance obtained from testing under static loading would overestimate the DIF.

Concrete contribution v_c to shear stress

To evaluate the concrete contribution to the shear resistance, only SR beams were considered and collected from the published database and the current testing data. ACI 318-08¹⁴ only provides the coefficients of concrete contribution to shear stress normalized by the square root of concrete compressive strength (that is, 0.17 and 2 for SI and U.S. unit systems, respectively) under static loading only. To incorporate the loading rate effects of concrete contribution to shear stress, the testing shear resistance values are normalized by the square root of concrete compressive strength, the width, and the effective depth of beams. Figure 9 displays the variation of concrete contribution to shear stress normalized by the square root of the concrete compressive strength ($v_c/\sqrt{f'_c}$) under different loading rates (δ). Few erratic data were observed in the data provided by Mutsuyoshi and Machida.⁴ Yielding of the tensile reinforcing bar after the shear failure of the beam could be the reason behind this inconsistent behavior.

Fig. 10—Concrete and shear reinforcement contribution to shear resistance. (Note: 1 kN = 0.225 kip; 1 m/s = 3.28 ft/s.)

Fig. 11—Cracking stiffness of: (a) $a/d = 3.3$; and (b) $a/d = 4.4$ series beams under varying loading rates.

Concrete V_c and shear reinforcement V_s contribution to shear resistance

Figure 10 shows the concrete and shear reinforcement contribution to shear strength of DR beams of $a/d = 3.3$ series, as the specimens of this series failed in shear irrespective of loading rates. A crude estimation was performed to calculate the corresponding contribution to shear resistance. Concrete contribution has been taken from SR beams of the same series, as shear force was solely resisted by concrete. To account for the stirrup contribution, shear resistance of the SR beams has been deducted from the shear resistance of DR beams of the same series by neglecting the contribution of compression reinforcement to shear strength. From Fig. 10, it is evident that the shear reinforcement contribution as compared with concrete contribution is much less under these four varying loading rates.

Cracking stiffness

Cracking stiffness of the beams was calculated by using the secant of the load-versus-midspan deflection curve passing through the point from which the curve changes its slope. It was then simply computed by taking the quotient of the resistance and the deflection of that corresponding point. Figure 11 displays the variation of cracking stiffness of the two series (that is, $a/d = 3.3$ and 4.4) of specimens. Enhancement in cracking stiffness of $a/d = 3.3$ series specimens was observed when the loading rate increased from static to low and medium rates. Similarly, for $a/d = 4.4$ series specimens, stiffness increases as the loading rate progresses from static to medium. Figure 11, however, lacks the stiffness under high rates as the load-versus-midspan deflection curves were obtained in this case by deducting the inertia force from the top load cell. Due to the time lag between the top and bottom load-cell signals, the response obtained from the bottom load cells under high rates may not be similar to the

Table 2—Comparison between time to reach peak load and yielding of tensile and shear reinforcements

Specimens	Time	Static, s	Low, s	Medium, ms	High, ms
SR3.3_0.84	T_{pl}	362.5	0.22	20	3.3
DR3.3_0.84_0.11		181.4	0.5	34	5.7
DR3.3_0.84_0.15		188.4	0.57	36	5.4
	Average	SA1,2	SA1,2	SA1,2	SA1,2
SR3.3_0.84	T_{ytl}	359.3	0.125	11.4	1.84
DR3.3_0.84_0.11		174.9	0.084	12.2	1.49
DR3.3_0.84_0.15		183.6	0.095	11.6	1.68
	Average	SS1,2	SS1,2	SS1,2	SS1,2
DR3.3_0.84_0.11	T_{ys}	152.3	0.32	NY	4.2
DR3.3_0.84_0.15		NY	NY	NY	1.21

Note: T_{pl} is time to reach peak load; T_{ytl} is time to yield longitudinal tensile reinforcing bar; T_{ys} is time to yield shear reinforcing bar; NY is not yielded.

same from the top load-cell. The reason behind this time lag could be due to the inertia forces, as the initial force applied is solely resisted by the inertia of the beam before the bottom load-cell attained any load.

Energy absorption

To calculate the amount of energy absorption of the specimens under these varying loading rates, the area under the load-versus-midspan deflection curves needs to be calculated. Before that, the generalized midspan displacement range should be defined to impose the same conditions for all the specimens. The deformation range was defined up to peak load displacement (for shear-failure type beams) or three times the yield deformation (for flexure-failure type beams), solely depending on the characterization of their load-versus-midspan deflection curves. For medium and high loading rates, however, the load-midspan deformation curves did not display the yield plateau. For these cases, peak load displacement has been taken as benchmark point. Figure 12 clearly illustrates the variation of the energy absorption capacity of RC beams for static, low, medium, and high loading rates. The energy absorption capacity of the RC beams increased with the enhancement of loading rates from static to high.

Comparison of time to reach peak load, yielding of tensile and shear reinforcements, and peak strain rate

Table 2 represents the comparison between the time to reach peak load and yielding of tensile and shear reinforcements for 3.3 series specimens, as these specimens failed in shear at their ultimate resistance. It is worthwhile to know whether the longitudinal and shear reinforcing bars yielded before or after attainment of the peak resistance. From this table, it is clear that except for static loading, the tensile reinforcements yielded at very early stages for all loading rates. If the tensile reinforcing bars yielded before the shear failure, the DIF would be less than the case of yielding of the same after shear failure. Only a few cases, however, were seen

Fig. 12—Energy absorption of: (a) $a/d = 3.3$; and (b) $a/d = 4.4$ series beams.

Fig. 13—Maximum strain rate of: (a) longitudinal; and (b) shear reinforcing bars for all specimens.

where the shear reinforcing bar yielded before shear failure or did not yield at all. Due to the larger spacing of shear reinforcing bars, diagonal shear cracks did not intersect them (that is, propagated in between stirrups). Additionally, strain rate was calculated from the strain history data of longitudinal and shear reinforcements. The variation of peak strain rate over these loading rates for longitudinal and shear reinforcements are indicated in Fig. 13(a) and (b), respectively.

Deflected shapes

As mentioned previously, accelerometers were placed on the test specimens along the entire length on their top face in between the support points. Assuming zero displacement at support, the displacement time history of each point could be determined by double integrating the acceleration data. For a particular time, these data points are plotted and joined together by smoothened lines to get the deflected shape of the beams. Figure 14 displays the deformed shapes of the beams in 2.5 ms intervals for high loading rates. This figure distinctly shows the one-sided shear failure of $a/d = 3.3$ series specimens and flexure-type failure of $a/d = 4.4$ series specimens. Thus, the failure pattern can be observed in the deflected shapes of the beams at any time of the loading history. To obtain a more precise deflected shape of the beams, however, closely placed accelerometers should be installed.

Cracking patterns

Figure 15 shows the crack patterns of all specimens except DR4.4_0.82_0.19_L under these loading rates. SR beams of the 3.3 series exhibited brittle shear-critical behavior, irrespective of loading rates. Diagonal shear cracks originated from the midheight of the beam and propagated towards loading and support points for all loading rates. For DR specimens, however, diagonal shear cracks under medium

Fig. 14—Deflected shape of: (a) $a/d = 3.3$; and (b) $a/d = 4.4$ series specimens under high loading rates. (Note: 1 mm = 0.04 in.)

and high loading rates propagated with much steeper angles towards the bottom surface of the beam as compared with static and low loading rates. In these cases, diagonal cracks under medium and high loading rates tried to punch the mid-part of the specimens towards bottom surface of the beam at steep angles as the shear reinforcements gave resistance to transmit these cracks towards supports. In general, for the 3.3 series of specimens, diagonal tension and/or shear tension type failure was observed in SR beams, whereas diagonal tension and/or shear compression were the dominant failure modes for DR specimens. It was observed that all 3.3 series specimens failed in shear at their peak resistance; however, measurement of steel strain data exhibited the yielding of tensile reinforcing bars before peak load or shear failure occurred for low, medium, and high loading rates. Development and propagation of cracks around different points in load-versus-time curves were portrayed in Fig. 16 for SR3.3_0.84 under high loading rates. Two explanations could be used to justify the shear failure of DR3.3 series specimens under a high loading rate. One is the wider spacing of web reinforcements, and the other is the increment of flexural resistance of beams under low, medium, and high loading rates due to strain rate sensitivity of yield stress of tensile reinforcing bars. Considering the DIF of yield stress of tensile reinforcing bars, it was calculated that flexural resistance increased approximately 18.5, 21.3, and 24.8% for the aforementioned loading rates as compared with assuming static yield stress for all rates. Strain rate

sensitivity of yield stress of stirrups, however, did not contribute much (in the majority of cases, stirrups did not yield) to their shear resistance. As a result, the shear-bending resistance ratios became in the range of 0.9 to 1, which were 1.1 to 1.2 at the initial design stage (considering static yield stress). For 4.4 series specimens, ductile-flexure type failure was observed for all loading rates. In these cases, flexural cracks usually started from the bottom surface of the beam and propagated vertically upwards and successively crushed the compression concrete.

CONCLUSIONS

1. A comprehensive review on the effects of high loading rate on RC beams is presented. Due to the scattered data points, it is difficult to draw a conclusion on the effects of any single parameter on DIF of SR beams. For a DR section, prominent influence on DIF under high rates has been visualized for short beams as compared with slender beams; the beams with less shear reinforcements had higher DIFs for high rates as compared with beams with higher shear reinforcements. Furthermore, it was observed that shear critical beams produced higher DIF as compared with flexure critical for all loading rates. If the tensile reinforcing bars yielded before the shear failure, the DIF would be less than the case of yielding of the same after shear failure. Additionally, several issues related to high-rate testing (that is, testing setups, anchorage types, and different material properties) have been discussed after reviewing the wide dispersion of

Fig. 15—Cracking patterns of: (a) $a/d = 3.3$; and (b) $a/d = 4.4$ series specimens under varying loading rates.

results in terms of DIF and the difference in change of failure mode. Therefore, identical specimens should be tested under varying loading rates using various hydraulic machines to identify the actual reason of inconsistency in the results. It would then be more realistic to incorporate some provisions in the ACI code regarding the influence of loading rates on structural elements.

2. From the current testing program, with increasing loading rates, the ultimate load resistance, cracking stiffness, and energy absorption of RC beams were found to increase. When the loading rate progressed from low to high, an increasing trend in DIF was observed. In addition, specimens

with a smaller a/d produced a higher DIF as compared with the specimens with a higher a/d for low, medium, and high loading rates. For instance, 3.3 series specimens had higher DIFs as compared with the 4.4 series. Moreover, for low, medium, and high loading rates, if the tensile reinforcing bars yielded before the shear failure, the DIF would be less than the case where yielding of tensile reinforcing bars was followed by the shear failure. For the first case, strain rate sensitivity of yield stress of reinforcing bars controls the magnitude of DIF, whereas strain rate sensitivity of the tensile strength of concrete controls the magnitude of DIF for the second case. The tensile strength of concrete is more

Fig. 16—Development of cracks in SR3.3_0.84 under high loading rates.

rate sensitive than yield stress of reinforcing bars; thus, the DIF is higher for the second case.

3. High loading rates seem to have a beneficial effect on shear resistance, as concrete contribution increases with increasing loading rates. Analysis response revealed that compared with shear reinforcement contribution, concrete contribution governs in shear resistance contributions under these loading environments.

4. For the 3.3 series specimens, diagonal tension and/or shear tension type failure was observed in SR beams, whereas diagonal tension and/or shear compression were the dominant failure modes for DR specimens. In all loading rates of the aforementioned series, diagonal shear cracks originated from the midheight of the beam and propagated towards loading and support points. For DR specimens, however, diagonal shear cracks under medium and high loading rates propagated with much steeper angles towards the bottom surface of the beam as compared with static and low loading rates. On the other hand, for the 4.4 series specimens, ductile flexure type failure was observed for all loading rates.

5. Future research could be accomplished with several key focuses, such as the effect of high loading rates on high-strength concrete beams, and beams with various sizes and boundary conditions. Moreover, beams under asymmetrical high loading rates could be taken into account.

AUTHOR BIOS

Satadru Das Adhikary is a PhD Student in the Natural Hazards Research Center (NHRC) at Nanyang Technological University, Singapore. He received his BEng from Bengal Engineering and Science University, West Bengal, India. His research interests include reinforced concrete structures under varying rates of concentrated and impact loading.

ACI member Bing Li is an Associate Professor and Director of NHRC at Nanyang Technological University. He received his PhD from the University of Canterbury, Christchurch, New Zealand. His research interests include structural concrete, particularly in design for earthquake and blast resistance.

ACI member Kazunori Fujikake is a Professor in the Department of Civil and Environmental Engineering at the National Defense Academy of Japan, Kanagawa, Japan. He received his BS, MS, and PhD from the University of Tsukuba, Japan. He is a member of ACI Committee 370, Blast and Impact Load Effects. His research interests include the mechanical properties of cementitious materials under dynamic loadings and the structural performance of reinforced concrete structures under impact and blast loadings.

REFERENCES

1. Saatci, S., and Vecchio, F., "Effects of Shear Mechanism on Impact Behavior of Reinforced Concrete Beams," *ACI Structural Journal*, V. 106, No. 1, Jan.-Feb. 2009, pp. 78-86.
2. Kishi, N.; Mikami, H.; Matsuoka, K. G.; and Ando, T., "Impact Behavior of Shear-Failure Type RC Beams without Shear Rebar," *International Journal of Impact Engineering*, V. 27, 2002, pp. 955-968.
3. Fu, H. C.; Erki, M. A.; and Seckin, M., "Review of Effects of Loading Rate on Reinforced Concrete," *Journal of Structural Engineering*, ASCE, V. 117, No. 12, Dec. 1991, pp. 3660-3679.
4. Mutsuyoshi, H., and Machida, A., "Properties and Failure of Reinforced Concrete Members Subjected to Dynamic Loading," *Transactions of the Japan Concrete Institute*, V. 6, 1984, pp. 521-528.
5. Kulkarni, S. M., and Shah, S. P., "Response of Reinforced Concrete Beams at High Strain Rates," *ACI Structural Journal*, V. 95, No. 6, Nov.-Dec. 1998, pp. 705-715.
6. Fujikake, K.; Li, B.; and Soeun, S., "Impact Response of Reinforced Concrete Beam and Its Analytical Evaluation," *Journal of Structural Engineering*, ASCE, V. 135, No. 8, Aug. 2009, pp. 938-950.
7. Bischoff, P. H., and Perry, S. H., "Compressive Behavior of Concrete at High Strain Rates," *Materials and Structures*, V. 24, May 1991, pp. 425-450.
8. Fu, H. C.; Erki, M. A.; and Seckin, M., "Review of Effects of Loading Rate on Concrete in Compression," *Journal of Structural Engineering*, ASCE, V. 117, No. 12, Dec. 1991, pp. 3645-3659.
9. Malvar, L. J., and Rose, C. A., "Review of Strain Rate Effects for Concrete in Tension," *ACI Materials Journal*, V. 95, No. 6, Nov.-Dec. 1998, pp. 735-739.
10. Malvar, L. J., "Review of Static and Dynamic Properties of Steel Reinforcing Bars," *ACI Materials Journal*, V. 95, No. 5, Sept.-Oct. 1998, pp. 609-616.
11. Adhikary, S. D.; Li, B.; and Fujikake, K., "Dynamic Behavior of Reinforced Concrete Beams under Varying Rates of Concentrated Loading," *International Journal of Impact Engineering*, V. 47, 2012, pp. 24-38.
12. Adhikary, S. D.; Li, B.; and Fujikake, K., "Strength and Behavior in Shear of Reinforced Concrete Deep Beams under Dynamic Loading Conditions," *Nuclear Engineering and Design*, V. 259, 2013, pp. 14-28.
13. Fujikake, K.; Li, B.; Adhikary, S. D.; and Salem, H. M., "Dynamic Shear Resistance of Short RC Beams," *Fourth International Conference on Design and Analysis of Protective Structures*, Jeju, Korea, 2012, pp. 19-22.
14. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary," American Concrete Institute, Farmington Hills, MI, 2008, 473 pp.

APPENDIX

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
Mutsuyos	A 1-S	29.0	200	150	160	880	5.5	0.89 ^T	382	-	-	1x10 ⁻⁴	23.6	Flexur

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
hi & Machida	A 1-D									-	-	2.63x10 ⁻¹	30.8	e

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
(1984)	A 2-S	32.7						1.70 ^T	377	-	-	5x10 ⁻⁵	45.0	
	A 2-D									-	-	2.2x10 ⁻¹	55.0	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
		h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)				
	A 3-S	31.9						2.39 ^T	361	-	-	5x10 ⁻⁵	57.9	Shear
	A 3-D									-	-	2.16x10	70.8	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	A 4-S	34				448	2.8	0.89 ^T	432	-	-	3x10 ⁻⁵	51.7	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	A 4-D								-	-	2.33x10 ⁻¹	72.4		

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
								h (mm)	b (mm)					
	A 5-S	35.1				496	3.1	1.05 ^T	381	-	-	3x10 ⁻⁵	50.3	
	A 5-D									-	-	1.15x10	71.5	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
											-1			
	A 6-S	34				752	4.7	1.70 ^T	360	-	-	2x10 ⁻⁵	45.4	Flexur

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	A 6-D									-	-	2.18x10 ⁻¹	59.8	e

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
								h (mm)	b (mm)					
		A 7-S	31.6				784	4.9		393	-	-	5x10 ⁻⁵	49.0
A 7-D									-	-	2.3x10 ⁻¹	61.6		

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	B 1-S	26.8	150	100	120	684	5.7	2.11 ^T	456	-	-	2x10 ⁻⁵	23.6	Flexure

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	B 1-D									-	-	7.63x10 ⁻¹	36.5	Shear

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	B 2-S	28.6				564	4.7	1.78 ^T	398	-	-	3x10 ⁻⁵	30.4	Flexure
	B 2-D									-	-	1.67x10	38.2	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	B 3-S	23.2				480	4.0	1.19 ^T	398	-	-	2x10 ⁻⁵	25.5	Flexur

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
								h (mm)	b (mm)					
														e
	B 3-D									-	-	2.67x10	31.3	Shear

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)		a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)			
	B 4-S	28.6				588	4.9	1.78 ^T	393	-	-	3x10 ⁻⁵	27.9	Flexur

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	B 4-D								-	-	5.67x10 ⁻¹	33.7	e	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	B 5-S	28.0				456	3.8	2.11 ^T	506	-	-	1.43x10 ⁻¹	49.2	Shear

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	B 5-D									-	-	2.77x10 ⁻¹	47	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
								h (mm)	b (mm)					
		C 1-S	23.7	150	100	120	684	5.7	4.78 ^T	320	-	-	2x10 ⁻⁵	33.4
C 2-D	-	-									1.89x10	50.3		

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode	
								Tensile (T) & Compressive (C)							
								h (mm)	b (mm)						d (mm)
	Ratio (%)		f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)										
												-1			
	C 3-D									-	-	4.08x10	52.6		

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
											-1			
Kulkarni	B4JL25-S	41.5	178	102	152	836	5.5	1.37 ^T	518	-	-	7.1x10 ⁻⁶	41.7	Flexur

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
& Shah (1998)	B4JL25-H	41.5				836	5.5					3.8x10 ⁻¹	46.4	e
	B3OC25-S	46.2				760	5					7.1x10 ⁻⁶	40.5	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	B3OC25-H	46.2				760	5					3.8x10 ⁻¹	46.7	
	B4JL20-S	41.9				760	5					7.1x10 ⁻⁶	39.1	Shear

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	B4JL20-H	41.9				760	5					3.8x10 ⁻¹	44.9	Flexure

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	B3SE03-S	45				684	4.5					7.1x10 ⁻⁶	45.9	Shear
	B3SE03-H	45				684	4.5					3.8x10 ⁻¹	51.6	Flexur

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	B3DE03-S	43				684	4.5					7.1x10 ⁻⁶	45.3	e
	B3DE03-H	43				684	4.5					3.8x10 ⁻¹	50.9	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	B3NO15-S	43				608	4					7.1x10 ⁻⁶	43.9	Shear
	B3NO15-H	43				608	4					3.8x10 ⁻¹	56.8	Flexur

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
														e
	B3NO30-S	45				532	3.5					7.1x10 ⁻⁶	49.9	Shear

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	B3NO30-H	45				532	3.5					3.8x10 ⁻¹	55.8	Shear
Fujikake	S1616	42	250	150	210	700	3.33	1.27 ^{T&C}	426	0.5	295	5x10 ⁻⁴	115	Flexur

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
et al. (2009)	S1616							1.27 ^{T&C}	426			2x10 ⁰	135	e
	S2222							2.41 ^{T&C}	418			5x10 ⁻⁴	200	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	S2222						2.41 ^{T&C}	418			2x10 ⁰	243		
	S1322						2.4&0.	397			5x10 ⁻⁴	180		

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
								h (mm)	b (mm)					
							84							
	S1322							2.4&0.	397			2x10 ⁰	246	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
						84								

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth h ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm))	b (mm))	d (mm))	a (mm))	a/d	Ratio (%)	f _{yl} (MPa))	Ratio (%)	f _{ys} (MPa))			

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth h ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm))	b (mm))	d (mm))	a (mm))	a/d	Ratio (%)	f _{yl} (MPa))	Ratio (%)	f _{ys} (MPa))			

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)		a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)			
Adhikary et al.	RC3_S0_S1	40	250	150	210	700	3.33	2.41 ^{T&C}	371	0	342	4x10 ⁻⁴	93.2	Shear
	RC3_S0_S2											4x10 ⁻⁴	81.3	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
(2012)	RC3_S0_L1											4x10 ⁻²	105.8	
	RC3_S0_L2											4x10 ⁻²	102.5	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
			RC3_S0_M1											
	RC3_S0_M2											4x10 ⁻¹	126.1	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
			RC3_S0_H1											
	RC3_S0_H2											2x10 ⁰	147.1	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC3_S12_S1								0.12		4x10 ⁻⁴	120		
	RC3_S12_S2										4x10 ⁻⁴	120.5		

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
			RC3_S12_L1											
	RC3_S12_L2											4x10 ⁻²	139.5	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
								h (mm)	b (mm)					
	RC3_S12_M1											4x10 ⁻¹	156.2	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm))	b (mm))	d (mm))	a (mm))	a/d	Ratio (%)	f _{yl} (MPa))	Ratio (%)	f _{ys} (MPa))			
	RC3_S12_M 2											4x10 ⁻¹	164.7	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
								h (mm)	b (mm)					
	RC3_S12_H 1										2x10 ⁰	168.7		

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC3_S12_H 2											2x10 ⁰	180.9	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC3_S56_S1								0.56		4x10 ⁻⁴	200.4	Flexure	
	RC3_S56_S2									4x10 ⁻⁴	202			

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
			RC3_S56_L1											
	RC3_S56_L2											4x10 ⁻²	217.9	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC3_S56_M 1											4x10 ⁻¹	222.6	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
								h (mm)	b (mm)					
	Ratio (%)		f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)									
	RC3_S56_M2											4x10 ⁻¹	223.1	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
								h (mm)	b (mm)					
	RC3_S56_H1										2x10 ⁰			

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC3_S56_H 2											2x10 ⁰	226.5	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth h ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm))	b (mm))	d (mm))	a (mm))	a/d	Ratio (%)	f _{yl} (MPa))	Ratio (%)	f _{ys} (MPa))			

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
Fujikake et al.	RC1.9_S0_S1	40	250	150	210	700	1.9	2.41 T&C	371	0	342	4x10 ⁻⁴	138.4	Shear

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
(2012)	RC1.9_S0_S 2											4x10 ⁻⁴	170.1	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
								h (mm)	b (mm)					
	RC1.9_S0_L 1										4x10 ⁻²	215.6		

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC1.9_S0_L 2											4x10 ⁻²	246.5	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
								h (mm)	b (mm)					
	RC1.9_S0_M1										4x10 ⁻¹			

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC1.9_S0_M2											4x10 ⁻¹	-	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC1.9_S0_H 1											2x10 ⁰	353.6	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC1.9_S0_H 2											2x10 ⁰	-	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC1.9_S42_ S1									0.42		4x10 ⁻⁴	271.9	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC1.9_S42_S2											4x10 ⁻⁴	-	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC1.9_S42_L1											4x10 ⁻²	-	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm))	b (mm))	d (mm))	a (mm))	a/d	Ratio (%)	f _{yl} (MPa))	Ratio (%)	f _{ys} (MPa))			
	RC1.9_S42_L2											4x10 ⁻²	300.6	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm))	b (mm))	d (mm))	a (mm))	a/d	Ratio (%)	f _{yl} (MPa))	Ratio (%)	f _{ys} (MPa))			
	RC1.9_S42_M1											4x10 ⁻¹	361.3	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm))	b (mm))	d (mm))	a (mm))	a/d	Ratio (%)	f _{yl} (MPa))	Ratio (%)	f _{ys} (MPa))			
	RC1.9_S42_M2											4x10 ⁻¹	-	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
								h (mm)	b (mm)					
	RC1.9_S42_H1										2x10 ⁰	417		

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC1.9_S42_H2											2x10 ⁰	-	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC1.9_S84_S1									0.84		4x10 ⁻⁴	329.8	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC1.9_S84_S2											4x10 ⁻⁴	333.8	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC1.9_S84_L1											4x10 ⁻²	-	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC1.9_S84_L2											4x10 ⁻²	378.2	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC1.9_S84_M1											4x10 ⁻¹	419.4	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC1.9_S84_M2											4x10 ⁻¹	422.1	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
			h (mm)	b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)			
	RC1.9_S84_H1											2x10 ⁰	447.9	

Reference	Beam mark	fc' (MPa)	Beam dimensions				Shear span to eff. depth ratio	Longitudinal reinforcement		Shear reinforcement		Loading rate (m/s)	Ultimate resistance (kN)	Failure mode
								Tensile (T) & Compressive (C)						
	h (mm)		b (mm)	d (mm)	a (mm)	a/d	Ratio (%)	f _{yl} (MPa)	Ratio (%)	f _{ys} (MPa)				
	RC1.9_S84_H2											2x10 ⁰	445.5	