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Experimental Study on the Effects of a Loading Rate on the Shear Performance of an RC Beam

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Abstract

Three 200x320x2300mm RC beams were tested under three different loading conditions to investigate the effects of loading rate on the shear performance of RC beam. Tested at loading rate 10mm/1hr, RC Beam 1 represents specimen under normal loading while RC Beam 2 represents specimen under slow loading at loading rate 10mm/100hr from 60kN. Tested at loading rate 10mm/100hr from 100kN, RC Beam 3 represents specimen under both normal and slow loading. The results showed that RC Beam 1, 2 and 3 had diagonal cracking load of 134.1kN, 133.6kN and 133.9kN and had ultimate failure load of 137.5kN, 146.2kN and 161.6kN respectively. Although these results indicated similar diagonal cracking strength, slow loading had influences on the ultimate failure load and crack pattern. The locations of diagonal bending crack for RC Beam 1, 2 and 3 were approximately 350mm, 530mm and 390mm from the center of the beam on the failure side. The location of bending cracks was affected by slow loading rate. As a consequence, slow loading had significant effects on the location of diagonal cracks so that it increased the ultimate failure load.

INTRODUCTION

The sustained load problem could occur in old structure constructed decades ago especially underground structure such as tunnel. In the aged structure design based on old specification, shear stress might be higher than that of the recent structure. Under this circumstance, creep shear failure might occur in the concrete structure. Rüsch (1960) studied the effects of sustained loading and loading rate on compressive strength of concrete and found that sustained loading and slower loading rate resulted in lower ratio of concrete maximum stress to cylinder strength. Experimental work done by Sarkhosh et al. (2013) investigated shear capacity of reinforced concrete (RC) beams under sustained loading and revealed that sustained loading has no significant effect on the shear capacity. However, the loading and displacement measurement system by Sarkhosh et al. could be further improved to better understand shear performance. There are few other studies of sustained load on shear performance of RC beams and the results are inconclusive. With the improved system, different loading rates are one of the approaches to verify the sustained loading effects. Based on this consideration, the effect of loading rate on shear performance of RC beam was investigated by experimental work.

EXPERIMENTAL PROGRAM

Materials and mixture proportions. Table 1 lists the properties of the materials used in this study while Table 2 tabulates the mixture proportion for cylindrical specimens and RC beams. The water to cement ratios (W/C) adopted in this study is 0.50.

Table 1. Material properties

Materials	Type	Properties
Cement	Ordinary Portland Cement	Specific gravity: 3.04
		Specific surface area: 3650 cm2/g
Fine aggregate	Crushed quartz	Surface-dry specific gravity: 2.58
Coarse aggregate	Crushed gravel (20-05)	Surface-dry specific gravity: 2.62

Table 2. Mixture proportion

Name	W/C (%)	Design Value		s/a (%)	Unit Weight (kg/m^3)						
		Slump (cm)	Air (%)		W	C	S		G		AD
							S1	S3	G1	G3	
50NC-SL	50	8±2	4.5±1.5	44.6	170	340	503	271	537	440	SV10L

Abbreviation: water (W), sand (s), aggregate (a), gravel (G) and admixture (AD)

Cylindrical specimens and RC beams. Cylindrical specimens of diameter 100mm by height 200mm for compressive strength and Young's modulus test as well as specimens of diameter 150mm by height 200mm for splitting tensile test were prepared. The testing ages were 1, 3, 7, 28, 91, and at the loading age of the RC beams for all cylindrical specimens except day 1 for splitting tensile specimen. The size and dimension of the RC beams are shown in Figure 1 with tension reinforcement ratio of 0.8%. High strength deformed steel reinforcement (f_y=1062N/mm^2) was used in this study in order to induce shear failure.

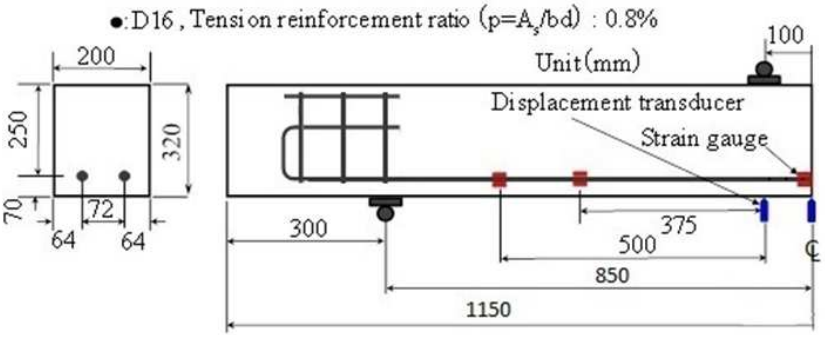


Figure 1. Outline of RC beams

Measurement system. Two concentrated load were applied on top of RC beams during testing at 100mm from center line on each side. The shear span to effective depth ratio was fixed to 3.0. Three displacement transducers were placed at the center of RC beams along bottom line to measure the average displacement. These transducers have capacity of measuring from 10mm to 50mm with minimum graduations of 0.001mm to 0.02mm. At the same time, these displacement transducers have a capacity of 25mm to 50mm with minimum graduations of 0.002mm to 0.005mm in diagonal tension direction. Additionally, they have capacity of 10 mm to 25 mm with minimum graduations of 0.001mm to 0.002mm in diagonal compression directions. Same type of transducers was used to measure vertical and horizontal displacements with capacity of 10mm to 50mm and minimum graduations of 0.001mm to 0.005mm. Displacement transducers for measurement of shear, vertical and horizontal displacements were installed on stainless steel beams with L-shape section. The details of installation of the displacement transducers are illustrated in Photo 1. Due to possibility of multiple cracks, crack widths were measured by π-shaped displacement transducers at every 100mm interval with capacity of 2 mm and minimum graduation of 0.001 mm as shown in Photo 1. Separate reinforcement strain gauges were installed at predetermined locations along reinforcement bar.

Photo 1. Overall view of RC beam set up

Loading condition of RC beam. Three RC beams were subjected to three different loading conditions until failure: normal loading rate at 10mm/1hr as RC beam 1, normal loading rate at 10mm/1hr until 60kN followed by slow loading rate 10mm/100hr as RC beam 2, and normal loading rate at 10mm/1hr until 100kN followed by slow loading rate 10mm/100hr as RC beam 3 as shown in Table 3. Before testing, all RC beams were carefully inspected and none were found to have any cracks. During testing, the development of cracks was checked at every 10kN interval until failure after 30kN mark in order to give a clearer understanding of loading rate effect. To avoid creep effect during every crack check, the load was manually decreased to approximately 5kN from the in-progress-load. Categorized as structurally crucial crack, diagonal crack was observed to begin its development between two key intervals: 60kN and 100kN.

Table 3. Loading conditions of RC beams

Representation	Normal Loading	Slow Loading	Normal & Slow Loading
	RC beam 1	RC beam 2	RC beam 3
Normal Rate: 10mm/1hr	0kN to ultimate failure	0kN to 60kN	0kN to 100kN
Slow Rate: 10mm/100hr	-	60kN to ultimate failure	100kN to ultimate failure

RESULTS AND DISCUSSION

Mechanical properties of concrete. The results of compressive strength, Young's modulus and splitting tensile strength are shown in Table 4. Both cylindrical specimens and RC beams were prepared and sealed using aluminum tape and cured under normal room temperature. Then, the seal were removed after 28 days so that drying effect on RC beams was minimized especially during testing at loading age.

Table 4. Mechanical properties of concrete

Age	Compressive Strength	Young's Modulus	Splitting Tensile Strength
(days)	(N/mm^2)	(kN/mm^2)	(N/mm^2)
1	13.0	21.0	-
3	23.6	27.2	2.59
7	29.3	29.7	2.98
28	35.1	31.9	2.94
91	40.4	31.1	3.44
130 (loading age)	39.8	29.7	3.28

Effects of loading rate. Starting from center line, one half portion of RC beam that diagonal crack occurred was referred as failure side and the other half portion was referred as non-failure side as indicated in Photo 4. Method to determine the precise diagonal cracking load value is generally considered as critical so the combination of on-site visual observation, load-deflection curve, and shear force-shear deflection relationship were applied in all of the three RC beams. RC beam 1 had diagonal cracking load and ultimate failure load of 134.1kN and 137.5kN while RC beam 2 had diagonal cracking load and ultimate failure load of 133.6kN and 146.2kN respectively. And RC beam 3 had diagonal cracking load and ultimate failure load of 133.9kN and 161.6kN as shown in Figures 2 and 3. From load and deflection curve, diagonal cracking load was observed by the noticeable decrease of load with respect to deflection. Although this trend was valid for all RC beams, RC beam 3 showed large increase in load and deflection afterward. After diagonal cracking load of 133.6kN, RC beam 2 failed at first failure load of 135.9kN with deflection of 6.14mm. Then, RC beam 2 showed increase in load and deflection again after 9.29mm deflection until ultimate failure load. This phenomenon is due to change of failure mechanism from failure side to non-failure side in the case of RC beam 2. As a consequence, failure side on the left span of RC beam 2 could be considered as first failure and non-failure side on the right span could be considered as second-failure as shown in Photo 4. Slow loading allowed more time for beam internal structure to response to loading. However, this change was not observed in case of RC beam 3 which represented normal and slow loading. At diagonal cracking load, RC beam 1, 2 and 3 had average deflection of 5.23mm, 5.68mm and 5.63mm at the beam center respectively. At ultimate failure load, displacement transducer at beam center showed that RC beam 1, 2 and 3 had average values of 6.14mm, 13.0mm and 8.25mm respectively. The values of diagonal cracking load are again confirmed by shear force-shear displacement relationship in Figures 4 and 5 for failure and non-failure side of RC beam. From shear force and shear displacement relationship, diagonal cracking load was observed by the noticeable decrease of shear force with respect to displacement. Although this trend was valid for all RC beams, RC beam 3 showed large increase in shear force and displacement afterward. This trend is similar to load and deflection curve of RC beam 3.

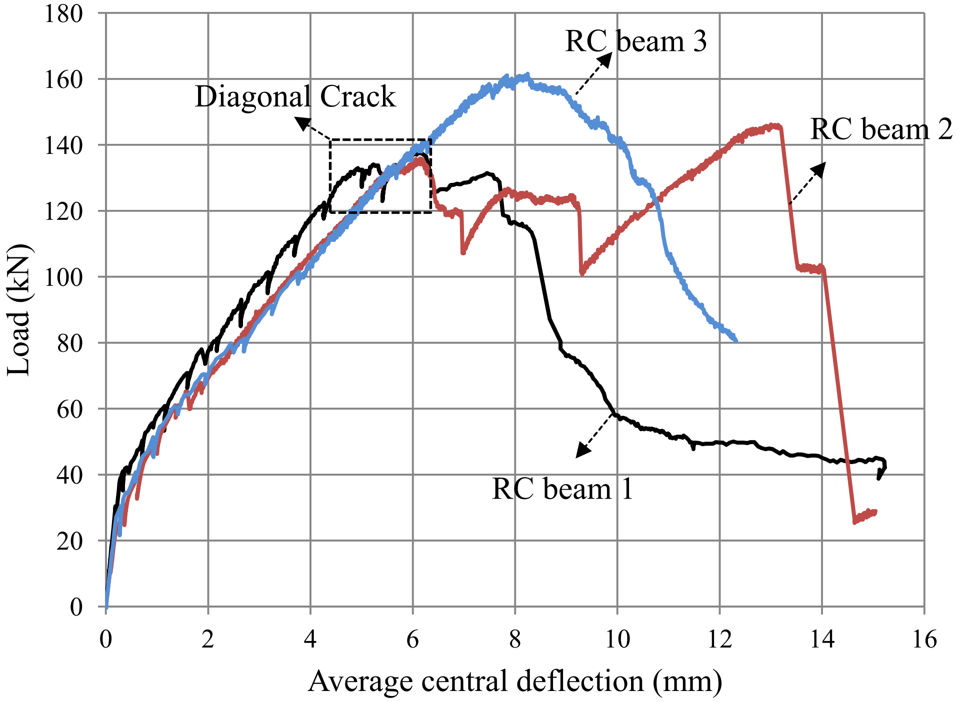
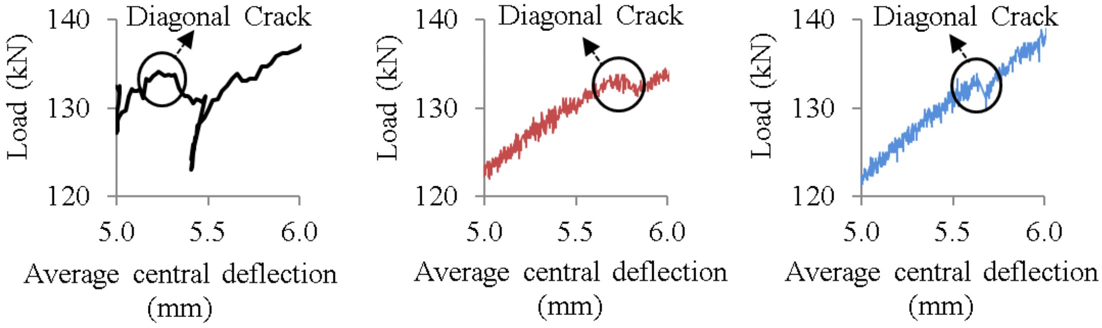
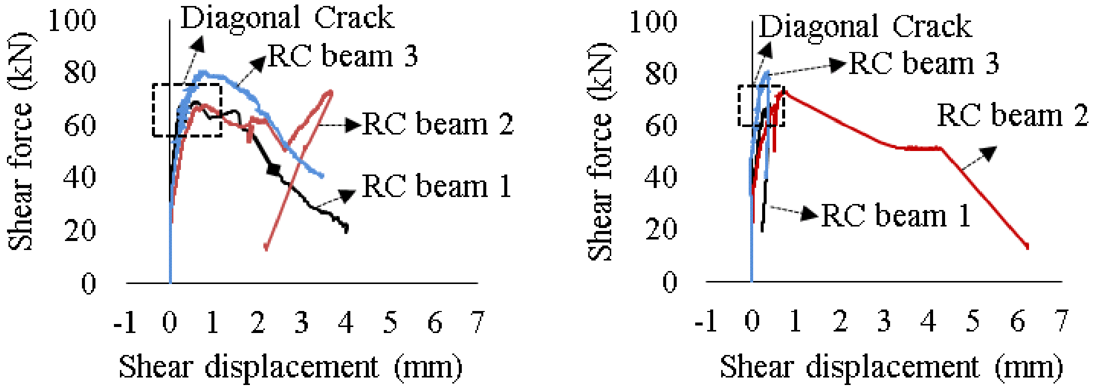


Figure 2. Load and average central deflection graph of RC beams



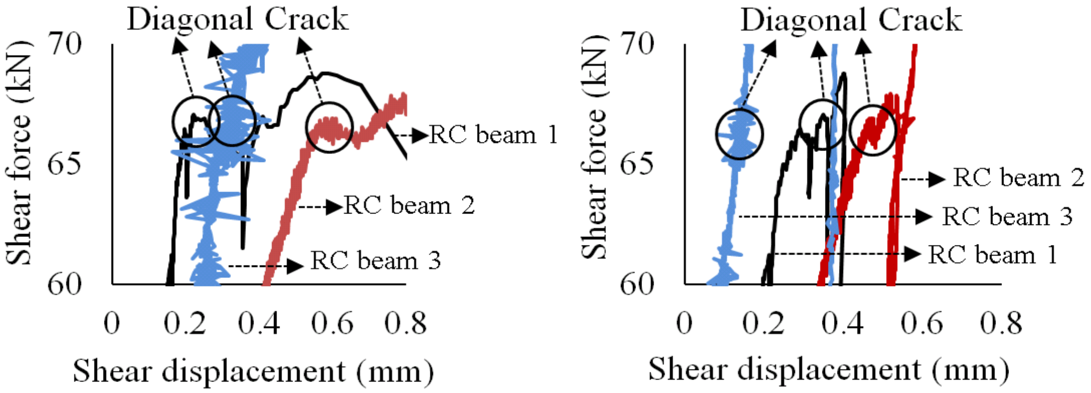
(a) RC beam 1 (b) RC beam 2 (c) RC beam 3

Figure 3. Close up view of diagonal cracking load of RC beams



(a) Failure side (a) Non-failure side

Figure 4. Shear force and shear displacement of RC beams



(a) Failure side (b) Non-failure side

Figure 5. Close up view of shear force and shear displacement at diagonal crack

The estimated and measured values of RC beam capacity with ratio of flexural cracking moment and diagonal cracking strength are shown in Tables 5 and 6. For flexural cracking load of RC beam 1, the measured value was higher than estimated value and it was difficult to explain the cause. For RC beam 2 and 3, the measured values were smaller than estimated value and this reduction might be the effect of shrinkage after seal removal. While the estimated value of diagonal cracking load is calculated using Niwa's equation, the ratios of estimated and measured value of diagonal cracking load are 1.23, 1.22 and 1.23 for RC beam 1, 2 and 3.

Table 5. Estimated values of RC beam capacity

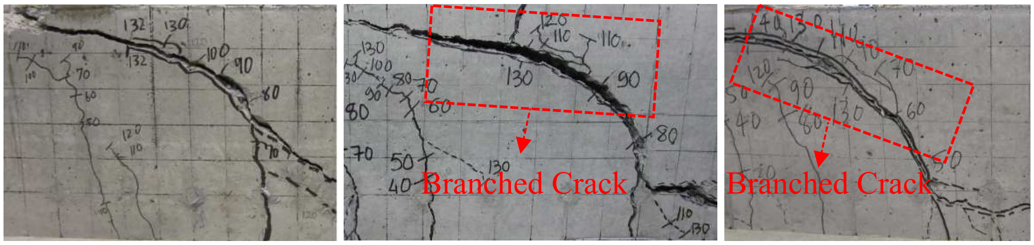
Specimen Name	Estimated values			
	Flexural cracking load	Flexural cracking moment	Diagonal cracking load	Diagonal cracking strength
	$P_{cr,calc}$	$M_{cr,calc}$	$V_{c,calc}$	$\tau_{c,calc}$
	kN	kNm	kN	N/mm^2
RC Beam 1	31.4	11.7	109.1	1.1
RC Beam 2				
RC Beam 3				

Table 6. Measured values of RC beam capacity

Specimen Name	Measured values					$M_{cr,exp}$/ $M_{cr,calc}$	$\tau_{c,exp}$/ $\tau_{c,calc}$
	Flexural cracking load	Flexural cracking moment	Diagonal cracking load	Diagonal cracking strength	Ultimate failure load		
	$P_{cr,exp}$	$M_{cr,exp}$	$V_{c,exp}$	$\tau_{c,exp}$	$P_{ult,exp}$		
	kN	kNm	kN	N/mm^2	kN	-	-
RC Beam 1	42.2	15.8	134.1	1.341	137.5	1.35	1.23
RC Beam 2	24.5	9.2	133.6	1.336	146.2	0.78	1.22
RC Beam 3	28.2	10.6	133.9	1.339	161.6	0.90	1.23

There are large differences of ultimate failure load between the three RC beams. Both RC beam 2 and 3 had higher ultimate failure load than RC beam 1. And, both RC beam 2 and 3 that were partially subjected to slow loading rate tends to have more branched crack pattern than normal loading RC beam 1 as shown in Photos 2 and 3. This branched crack can be explained by the fact that slow loading allows more time for beam internal structure to response to loading.

Photo 2. Overall view of cracked RC beams



(a) RC beam 1 (b) RC beam 2 (c) RC beam 3

Photo 3. Close up view of crack pattern of RC beams

Beside diagonal cracking load and central deflection, RC specimen 1, 2 and 3 had diagonal cracking distance of approximately 350mm, 530mm and 390mm from beam center as shown in Photo 4. Represented slow loading, RC beam 2 had bending crack much further from center of the beam than those of RC specimen 1 and 3.

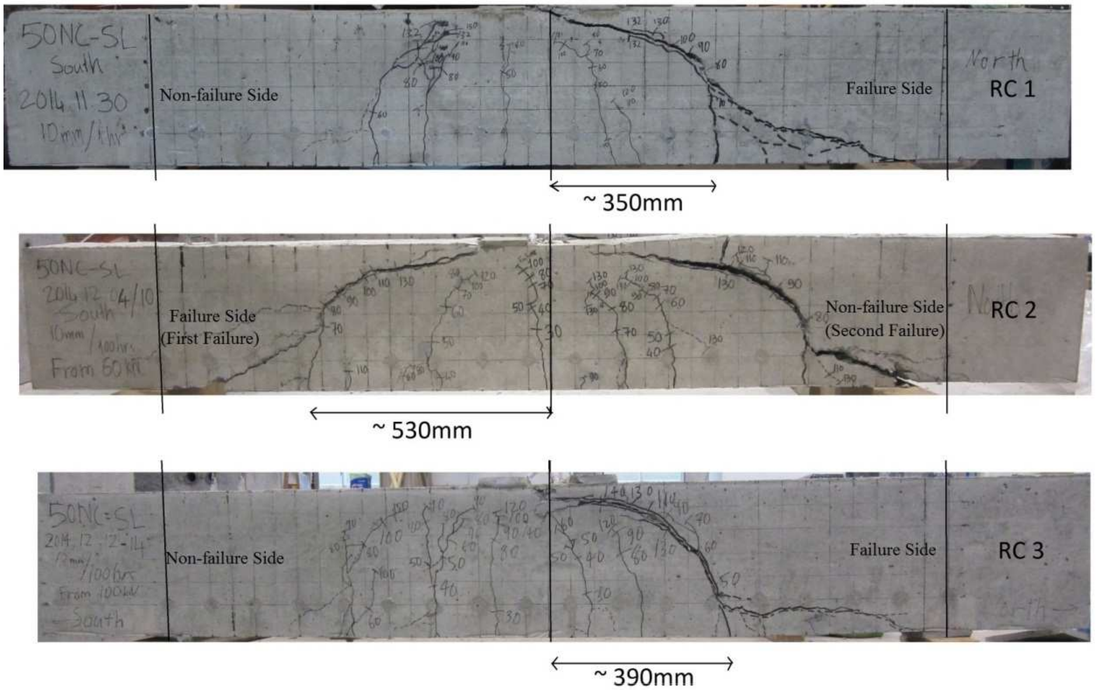


Photo 4. Location of diagonal crack and crack pattern of RC beams

CONCLUSION

Different loading rates were applied on three 200x320x2300mm RC beams to determine time-dependent effects on the shear performance. RC beam 1 represented specimen under normal loading while RC beam 2 represented specimen under slow loading. To better understand different loading rate, RC beam 3 was selected to represent specimen under slow and normal loading. Although these results indicated similar diagonal cracking load, slow loading had influences on the ultimate failure load. Slow loading allowed more time for internal beam structure to response to loading. In addition, slow loading rate affected the location of bending crack. At the same time, bending cracks directly affected diagonal cracks. As a consequence, slow loading had significant effects on the location of diagonal cracks. Within the boundary of this study, three unanswered facts are revealed about different loading rate on shear capacity of RC beam: no significant effect on diagonal cracking load, effect on ultimate failure load, and effect on location of diagonal crack. Due to limited number of testing, additional specimens are required to get more accurate results. Since all three RC beams were tested by displacement control setting, future study will use load control setting and the effects of load control setting on shear performance of RC beam will be studied.

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