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Experimental study on the ultimate strength of R/C curved beam

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ABSTRACT: The ultimate strength of a curved R/C beam is investigated experimentally. A curved R/C beam is classified as a statically indeterminate structure according to the structural boundary condition and is subjected to a torsion moment. The torsion moment generates diagonal tensile cracks on the concrete surface, when the beam is subjected to a lot of torsion. An appropriate arrangement of rebar is therefore recommended under such conditions. However, the ultimate torsion strength of an R/C member depends on a combination of several factors, so a universal theory should be established for the curved RC beam. Parameters adopted here are the radius of curvature, axial force, and shear span ratio. Then the influence of those parameters on the fracture behavior of the R/C curved beam was observed. From the experimental results, it was confirmed that the radius of curvature and axial force affect the fracture behavior of the R/C curved beam.

1 INTRODUCTION

In recent years, the curved beam has been adopted for large-scale concrete structures such as highway interchanges or a pre-stress concrete structure. A curved beam receives the torsion moment in order to keep the balance of the force in the whole structure against the perpendicular load, as shown in Figure 1. During an external force, such as an earthquake, a curved structure is subjected to a combined force that is composed of the axial force, the bending moment, the shear force, and the torsion.

When the curvature of a curved beam is small, the ultimate strength may be able to withstand the influence of the torsion moment. That is, the ultimate strength of the member in such a case is decided in either the ultimate moment or the ultimate shear strength.

On the other hand, ultimate shear strength of a reinforced concrete member goes up due to the axial compressive force. In the case of a curved beam, the influence of the axial compressive force for ultimate shear strength is not clear.

The authors have studied the ultimate strength of a reinforced concrete member subjected to the bending moment, the shear force, and the axial force. The relationship between ultimate shear strength and an axial force of the beam was clarified. Moreover, research on the curved beam was done focusing on the curvature.

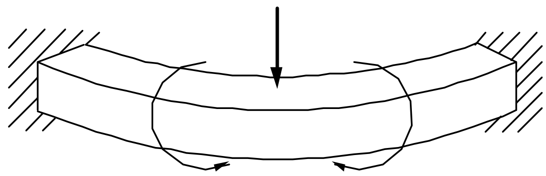


Figure 1. Curved beam.

In this research, the fracture properties of a reinforced concrete curved beam was studied experimentally as to the influence of axial force and shear span depth ratio.

2 EXPERIMENTAL PROGRAM

2.1 *Specimen*

Figure 2 shows the test beams. There are three types of specimens to discuss in terms of the relationship between each factor and the curvature. Nine specimens were provided. All of the specimens for experiment had the same dimensions. Two deformed bars (D13) were placed as the tensile reinforcement and the compressive reinforcement. Also, one round bar was arranged at the center of the cross-section to introduce the axial force. Eleven stirrups (Φ6) were placed at 15cm intervals.

The material properties of both the main and shear rebars are shown in Table 1. Table 2 shows the material properties of the concrete.

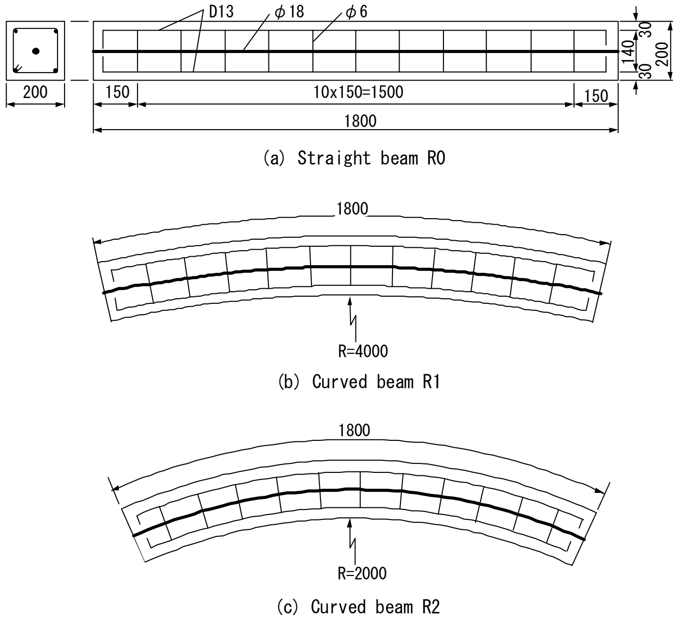


Figure 2. Cross-section of a curved beam.

Table 1. Material properties of rebar.

Rebar				
Rebar type			D10	ϕ 6
Elastic modulus	E_s	(GPa)	206	197
Tensile strength	f_u	(MPa)	529	581
Yield stress	σ_y	(MPa)	383	394

Table 2. Material properties of concrete.

Concrete			
Elastic modulus	E_c	(GPa)	24.9
Compressive strength	f_c'	(MPa)	29.6
Tensile strength	f_t	(MPa)	2.84

2.2 *Test apparatus and procedure*

The outline of the test is shown in Figure 3, and the test apparatus is shown in Figure 4. The apparatus is composed of an oil pressure actuator controlled by an electro-hydraulic servo mechanism. Both supporting points are fixed for vertical and horizontal directions and rotation as shown in Figure 5. In the case of the member being subjected to axial force, the axial compression is first introduced into both ends of the beam via a longitudinal jack and is held constant after reaching the expected compressive stress as shown in Figure 6. Next, the transverse loads are provided by a transverse actuator that can introduce the load into two points by the loading beam. The transverse load increases continuously until the beam fails under a displacement controlled system.

During the loading test, new cracks are marked on the face of the beam at each loading stage. Dial gauges are placed at the loading point and the center of the span to measure the deflection of the beam. Then the beam's strain is measured by wire strain gauges at the center of the tensile reinforcement and the top of the beam.

3 EXPERIMENTAL RESULTS

3.1 *Ultimate strength*

(1) Results about the relationship between shear span to depth ratio and curvature

Table 3 shows the experimental conditions and results. Figure 7 shows the relationships between ultimate strength and the shear span to depth ratio (a/d). When the shear span to depth ratio was 2.5, in all curvature, the ultimate strength went up almost similarly. The reason for this phenomenon is that the torsion moment of the curved beam became small in the case of a shear span to depth ratio of 2.5.

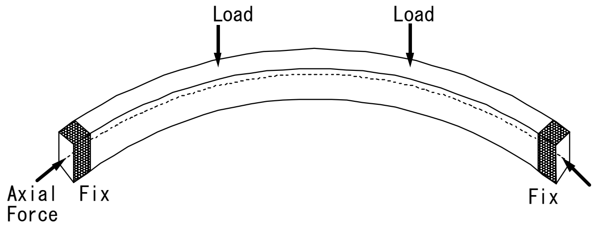


Figure 3. Outline of a curved beam.

Figure 4. Test apparatus and bending test of a curved beam.

Figure 5. Supporting point.

Figure 6. A jack for axial tensile compression.

Table 3. Test conditions and results (1).

Specimen	N (KN)	a/d	Pmax (KN)	Fracture mode
R0-N0-32	0	3.2	121.7	B
R1-N0-32	0	3.2	126.2	B
R2-N0-32	0	3.2	135.1	BS
R0-N0-25	0	2.5	163.9	BS
R1-N0-25	0	2.5	178.0	BS
R2-N0-25	0	2.5	170.0	BS

N: Axial force, a/d: Shear span depth ratio
Pmax: Ultimate strength
B: Bending failure, BS: Bending-shear failure

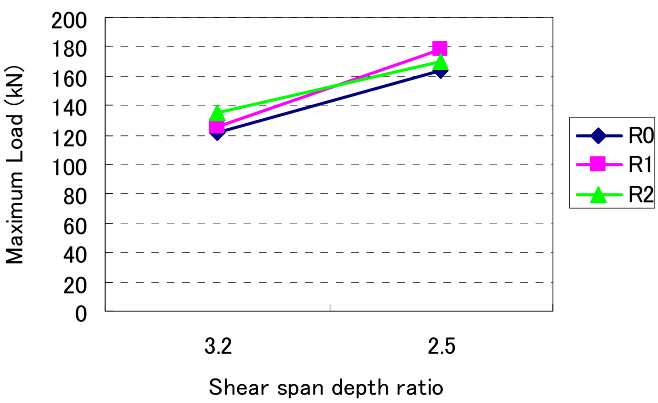


Figure 7. Relationship between ultimate strength and a/d.

(2) Results about the relationship between axial compression and curvature

Table 4 shows the experimental conditions and results. Figure 8 shows the relationships between ultimate strength and axial compressive strength. When the axial compressive force was applied to the straight line beam, the ultimate strength went up 5%. When the curvature was small, an increase of 31% of the ultimate strength was seen. However, when the curvature was big, the ultimate strength decreased 34%.

Table 4. Test conditions and results (2).

Specimen	N (KN)	a/d	Pmax (KN)	Fracture mode
R0-N0-32	0	3.2	121.7	B
R1-N0-32	0	3.2	126.2	B
R2-N0-32	0	3.2	135.1	BS
R0-N2-32	20	3.2	128.0	S
R1-N2-32	20	3.2	165.0	BS
R2-N2-32	20	3.2	101.0	S

N: Axial force, a/d: Shear span depth ratio
Pmax: Ultimate strength
S: Shear failure

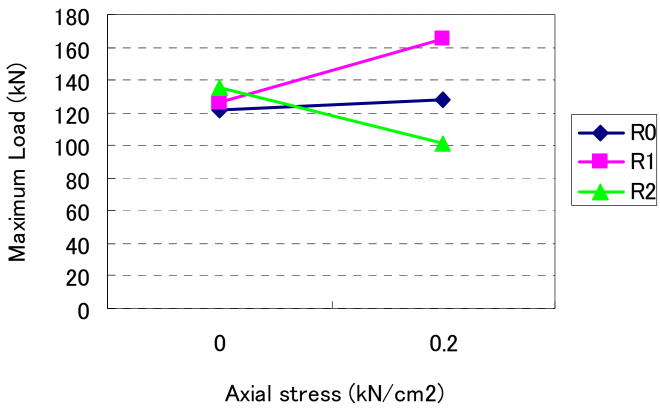


Figure 8. Relationship between ultimate strength and axial compression.

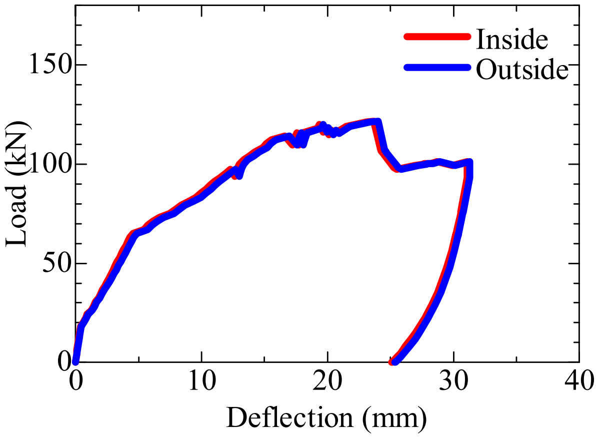
From this phenomenon, although the axial compressive force was small, the influence of the axial force is significant in the case of a curved beam.

3.2 *Load deflection relationships*

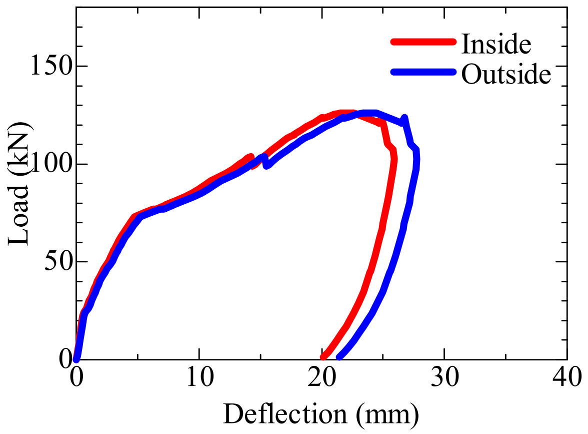
Figure 9 shows the load deflection relationship at the center of all beams. In the curved beam, outside displacement becomes larger than the inside displacement.

(1) Effect of shear span-to-depth ratio
At a shear span depth ratio of 3.2, the maximum displacement became large in the case of large curvature. However, at a shear span depth ratio of 2.5, the maximum displacement became small in the case of large curvature.

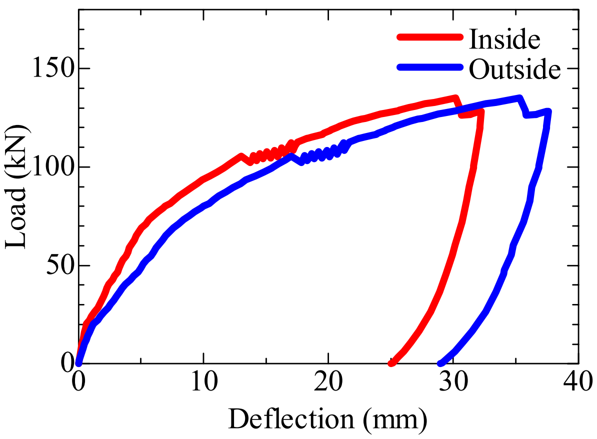
(2) Effect of axial compression
In a straight beam, when the axial compression was applied, the maximum displacement became small. With a small curvature beam, the maximum displacement was extended greatly. However, with a large curvature beam, the maximum displacement became small with the maximum load.



(a) R0-N0-32

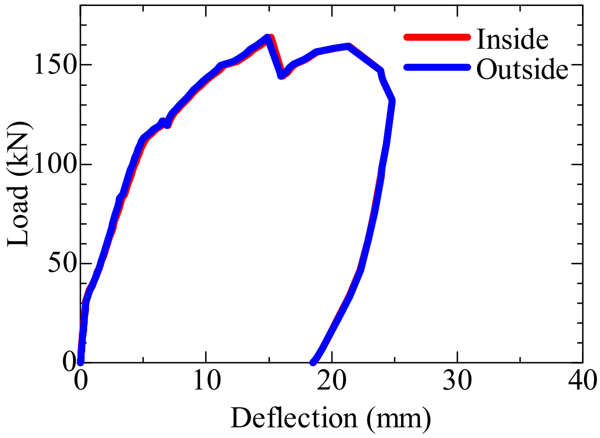


(b) R1-N0-32

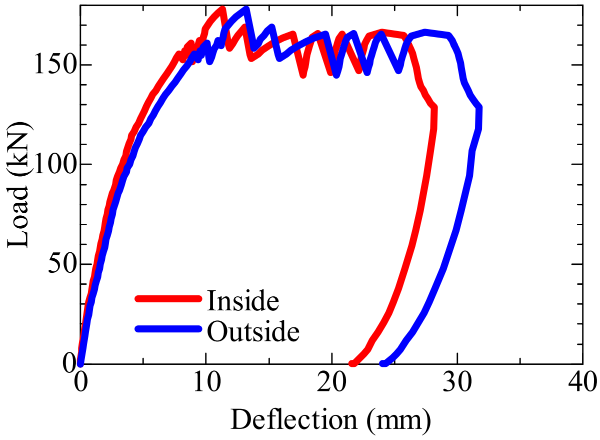


(c) R2-N0-32

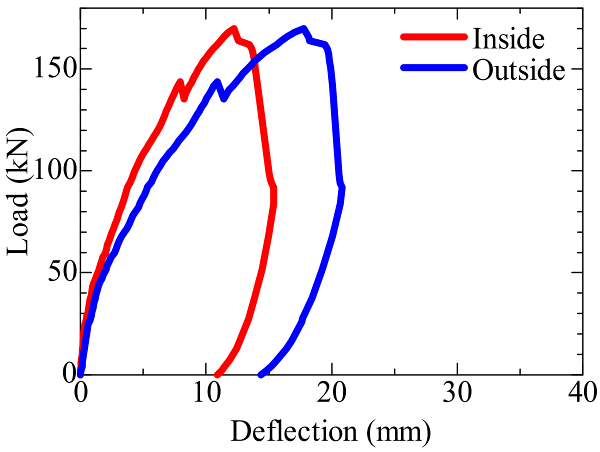
Figure 9. Relationship between load and deflection.



(d) R0-N0-25



(e) R1-N0-25



(f) R2-N0-25

Figure 9. Relationship between load and deflection.

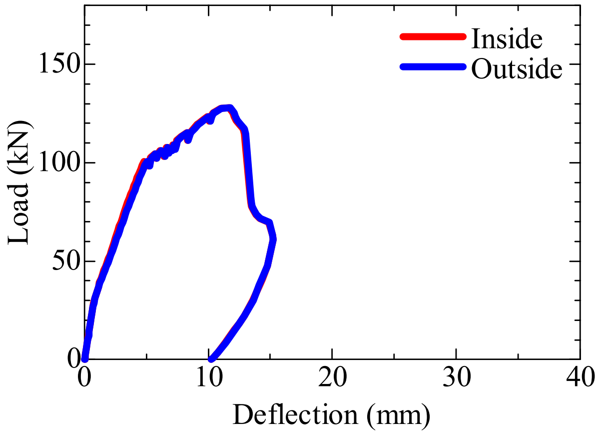
3.3 *Ultimate crack state*

(1) Results about the relation between shear span to depth ratio and curvature

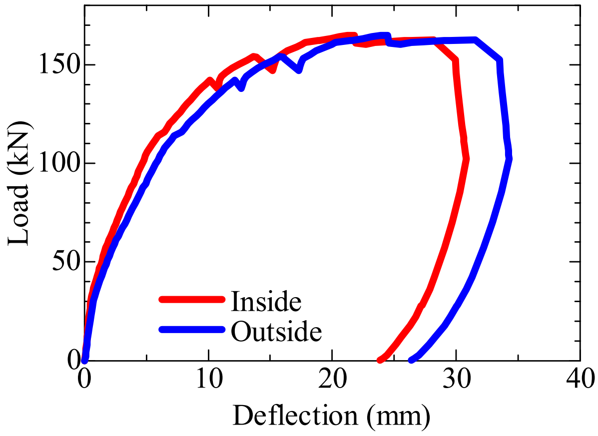
Figure 10 shows the fracture state of all beams. At a shear span depth ratio of 3.2, the members failed during bending, except the member with the large curvature. However, at a shear span depth ratio of 2.5, two torsion cracks influencing the torsion moment were observed.

(2) Results about the relationship between axial compression and curvature

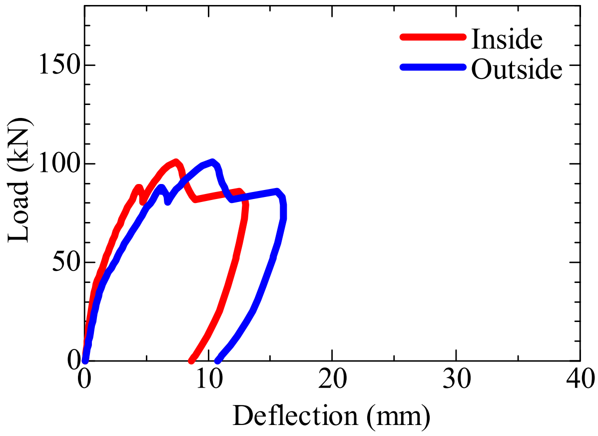
In case of the member subjected to axial compression, it was observed that the type R0 beam and type R1 beam fail during shear with diagonal cracks. However, when the small curvature R1 beam was subjected to the axial compression, the cracks occurred over a wide area. It was observed that the beam finally failed during compression at the concrete compressive area.



(g) R0-N2-32

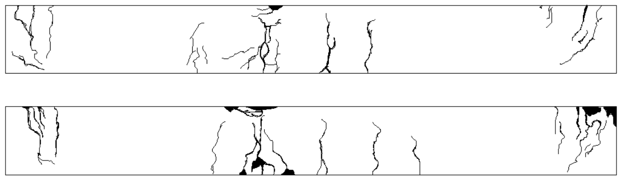


(h) R1-N2-32

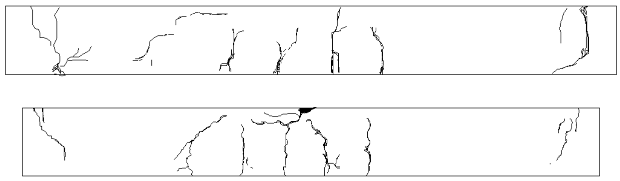


(i) R2-N2-32

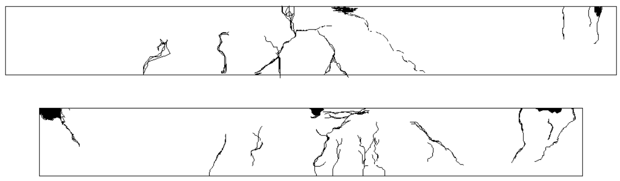
Figure 9. Relationships between load and deflection.



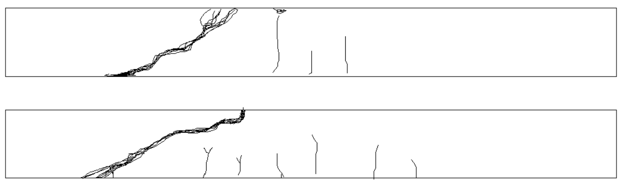
(a) R0-N0-32



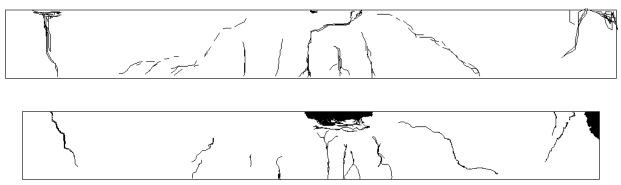
(b) R1-N0-32



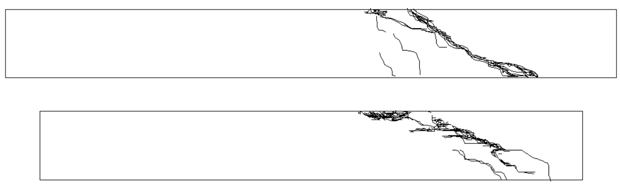
(c) R2-N0-32



(d) R0-N0-25



(e) R1-N0-25

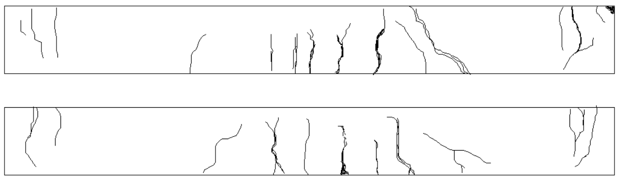


(f) R2-N0-25

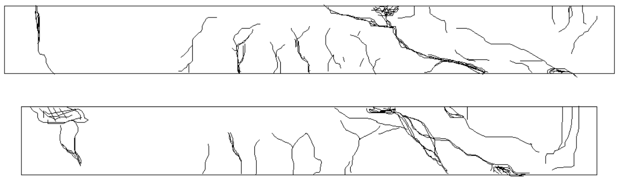
Figure 10. Fracture states.

4 CONCLUSIONS

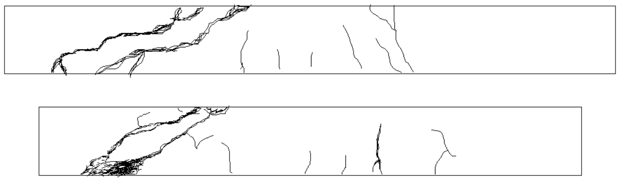
The fracture properties of the reinforced concrete curved beam were studied experimentally as to the influence of the axial force and the shear span depth ratio. Based on the test results, the following conclusions can be drawn:



(g) R0-N2-32



(h) R1-N2-32



(i) R0-N2-32

Figure 10. Fracture state.

(1) When the shear span to depth ratio changes, the rate of change of the ultimate strength of the curved beam is close to that of the straight beam.
(2) In a curved beam with a small curvature, the ultimate strength becomes large when axial compression was applied.
(3) However, in this experimental study, for the curved beam with large curvature, the ultimate strength became small when axial compression was applied.

It is important for resolving design problems for curved reinforced concrete beams that there is a close relationship between the curved beam and axial compression.

In order to resolve these problems, many more experiments are needed in future. In recent years, reinforced concrete member have been subjected to torsion and analyzed by numerical simulations. To achieve more accurate analysis, more experimental studies are necessary.

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