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Experimental Investigation on Flexural Behavior of Reinforced Concrete Curved Beams with different Types of Shear Reinforcement

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ABSTRACT: Reinforced Concrete (RC) curved beams are used for various structural applications and experimental study on the RC curved beams is essential to understand its behavior and failure criteria. Analysis of the RC curved beam is complex due to its geometry, boundary condition and it is also a statically indeterminate structure. In this study, the experimental investigation is carried out on Reinforced Concrete (RC) curved beam under combined flexural and fixed axial loading conditions in which the load-deflection behavior of RC curved beams is studied by varying span to depth ratio with constant width. Also, the effect of transverse shear reinforcement on the flexural behavior of the RC curved beam is studied for varying depth. Due to the high shear strength requirements, curved beams are usually constructed with large width as compared with straight beams. But in this study, different configurations of transverse shear reinforcement are introduced to develop an efficient section with constant width. Various types of transverse shear reinforcements used are spiral, vertical, horizontal, and zig-zag shear reinforcement. 6 sets of RC curved beams were cast and tested under combined two-point loading and fixed axial loading condition. From the experimental test results, it is observed that the introduction of horizontal and spiral shear reinforcement increases the load-carrying capacity of Reinforced Concrete curved beams for smaller sections.

Keywords: Horizontal stirrups, RC curved beam, Shear reinforcement, Spiral stirrups, Zig-zag stirrups.

Abbreviations: Reinforced Concrete (RC).

I. INTRODUCTION

Reinforced Concrete (RC) curved beams are widely used in many construction fields and it is also stated that curved beams are more productive than straight beams. There is expanding pattern among planners to move the conventional auxiliary pattern to complex spatial design using bent basic individuals. Curved beams are capable of exchanging loads through the combined action of twisting and bending. Beams curved in the plan are subjected to the torsional moment in addition to bending and shear under flexural loading conditions. Many research works have been carried out for studying the performance of Reinforced Concrete curved beams under different loading conditions. From the literature study, it is observed that curved beams with small curvature under axial compression and flexural loading have greater ultimate strength compared to curved beams with large curvature under axial compression and flexural loading. In addition to curvature, various parameters that affect the behavior of curved beams were identified as the depth of the section, the strength of the material, and boundary condition [3, 5]. The behavior of curved beam depends mainly on the angle of curvature in plan [4]. From the study conducted by Tan and Uy (2009), it is observed that the increase in the ratio of span/radius of curvature decreases ultimate flexural moment capacity of the composite beams, and also it is observed that the main failure criteria are due to the combined action of twisting and bending [2]. Tamura and Murata (2010) investigated the ultimate strength of a curved RC beam by conducting the parametric study. It is inferred from this study that the fracture behavior of RC curved beams is affected by the radius of curvature and axial force [6]. From the literature study, it is observed that there is limited research work carried out for developing an efficient section for curved beams. Hence the present study is carried out to determine the effect of shear reinforcement on the behavior of the RC curved beam with larger and smaller cross-sections.

II. RESEARCH SIGNIFICANCE

Nowadays architects prefer curved structural members while comparing with traditional straight structural members for modern space structures. Due to this reason, there is an increasing trend of using curved structural members in modern construction projects. But the analysis of such members is complex because curved structural members are subjected to the combined action of bending, shear, and torsion. Therefore, it becomes necessary to investigate the behavior of RC curved beams under different loading conditions. Hence in the present study, experimental work is carried out on RC curved beams provided with different types of shear reinforcement in both vertical and horizontal direction. Also, the efficient section for RC curved beams is developed by introducing different configuration of transverse shear reinforcement.

III. EXPERIMENTAL TESTING

M25 concrete grade is used for the present study, and the mix design is done as per IS: 10262 – 2009 [7] Cement was tested for basic properties such as initial setting time, final setting time, and specific gravity as per IS: 12269 [8]. The test results were found to be satisfactory. Fine and coarse aggregate was tested for specific gravity, fineness modulus, water absorption and moisture content as per Indian Standard specifications [9, 10]. Cube specimens of size 150 × 150 × 150 mm were cast and were tested for compressive strength and split tensile strength. Compressive strength (28 days) was 27.5 N/mm^2 and tensile strength (28 days) was 3.1 N/mm^2 and the results were found to be satisfactory. Hence, the curved beams are cast further with the arrived mix design ratio. For the present study, 12 curved beams were cast with varying span/depth ratio and constant width, length, and radius of curvature. Two sets of 6 beams are cast with 200 mm depth and 150 mm depth. The width of the beam is 150 mm; the radius of curvature is 2000 mm and the length of the beam is 1000 mm. The reinforcement bars used are of Fe 415 steel grade. The diameter of the longitudinal reinforcement bar used is 12 mm and for vertical stirrups, 8 mm diameter bar is used. A minimum diameter of 6 mm is used for horizontal stirrups. Horizontal stirrups are introduced in curved beams to take care of the twisting moment. Figs. 1 and 2 shows the reinforcement detailing of curved beams with a depth of 200 mm provided with vertical stirrups and beam with vertical stirrups and zig-zag horizontal stirrups.

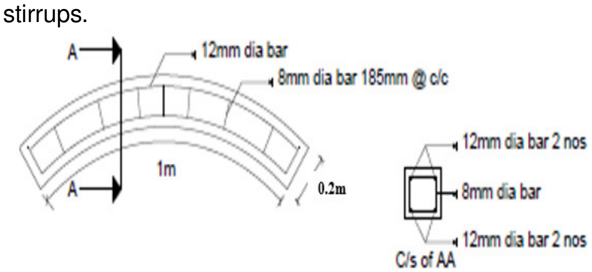

Fig. 1. A1 – Beam with normal vertical stirrups.

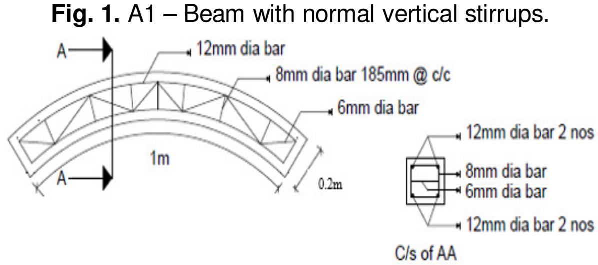

Fig. 2. A3 – Beam with vertical stirrups and zig-zag horizontal stirrups.

In the present study, different types of reinforcement are preferred because the curved beam behavior is completely variable compared to a normal straight beam. For the present study, 6 types of beams are analyzed to find better reinforcement configuration for field applications. Table 1 shows the details of the reinforcement configuration used in casting the RC curved beam. Fig. 3 shows the formwork with reinforcement for the A4 model.

Fig. 3. Formwork with reinforcement for A4 model.

Table 1: Details of Cast RC Beams.

Model No.	Depth (mm)	Configuration
A1	200	Normal vertical stirrups
A2	200	Vertical stirrups and horizontal stirrups
A3	200	Vertical stirrups and zigzag horizontal stirrups
A4	200	Spiral vertical stirrups
A5	200	Spiral vertical stirrups and horizontal stirrups
A6	200	Spiral vertical stirrups and zigzag horizontal reinforcement
A7	150	Normal vertical stirrups
A8	150	Vertical stirrups and horizontal stirrups
A9	150	Vertical stirrups and zigzag horizontal stirrups
A10	150	Spiral vertical stirrups
A11	150	Spiral vertical stirrups and horizontal stirrups
A12	150	Spiral vertical stirrups and zigzag horizontal reinforcement

Cast specimens were tested under a two-point flexural loading condition with the axial load applied through the hydraulic jack. The testing of curved beams is done similar to testing of conventional straight beams under two-point flexural loading [1]. A fixed axial load of 100 kN was applied through the axis of the beam using a hydraulic jack. Since the present study deals with a curved beam, the axial load was applied in addition to the flexural load. The experimental set up was arranged on the loading frame and the loading was applied at a rate of 2kN/min. The deflection was measured at mid-span of the beam by using a digital deflection transducer. The loading was increased until the specimen undergoes failure.

IV. RESULTS AND DISCUSSION

All 12 specimens were tested, and the results were compared for maximum deflection and ultimate load-carrying capacity. Specimens were tested for fixed axial load and varying two-point loading. Figs. 4 and 5 show the load-deflection curve for beams with a depth of 200 mm and 150 mm obtained from experimental results.

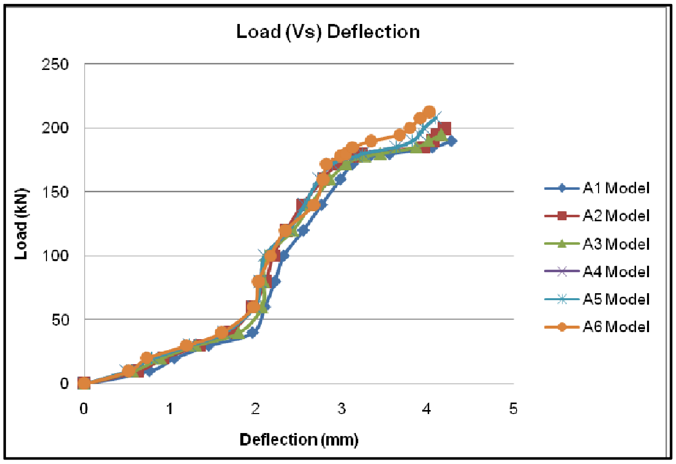

Fig. 4. Experimental load (vs) deflection for beam with depth of 200 mm.

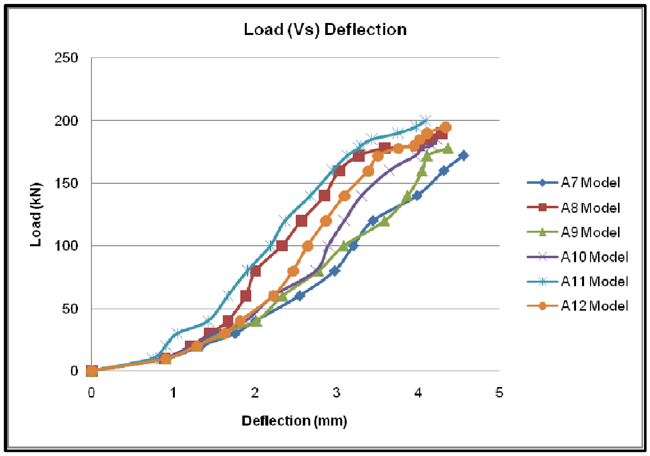

Fig. 5. Experimental load (vs) deflection for beam with depth of 150 mm.

Experimental test results such as maximum deflection and ultimate load are shown in Table 2 and 3. Table 2 shows the test results for curved beams with a depth of 200 mm and a span to depth ratio of 5. Table 3 shows the test results for curved beams with a depth of 150 mm and a span to depth ratio of 6.67.

From Table 2 and 3, it is observed that A5 and A11 specimens i.e. Specimen with spiral vertical stirrups and horizontal stirrups has an increase in load carrying capacity and decrease in deflection compared to curved beams with normal vertical stirrups. There is an increase in load-carrying capacity of A5 specimen by 12.6% compared to A1 specimen and deflection for A5 specimen is reduced by 8% compared to A1 specimen.

Table 2: Test results on curved beams (Depth – 200 mm)

Model	Maximum Deflection (mm)	Ultimate load (kN)	% increase in load carrying capacity w.r.t A1 specimen
A1	4.2	190	—
A2	4.19	201	5.8
A3	4.16	195	2.6
A4	4.09	208	9.5
A5	3.92	214	12.6
A6	4.02	213	12.1

Table 3: Test results on curved beams (Depth – 150 mm).

Model	Maximum Deflection (mm)	Ultimate load (kN)	% increase in load carrying capacity w.r.t A7 specimen
A7	4.70	172	—
A8	4.50	184	7
A9	4.25	179	4.1
A10	4.18	186	8.1
A11	4	200	16.3
A12	4.14	196	14

Also, from Table 3, it is inferred that there is an increase in load-carrying capacity for A11 specimen by 16% compared with A7 specimen, and deflection for A11 specimen is reduced by 10% compared with A7 specimen. The performance of the curved beam is improved by the introduction of spiral and horizontal stirrups in addition to vertical stirrups. Also, it is observed that load carrying capacity for A3 is less compared with A2 and load-carrying capacity for A6 is less compared with A5 specimen. From this observation, it is inferred that normal horizontal stirrups are preferred compared with zig-zag horizontal stirrups. Also, from Table 2 and 3, it is observed that the addition of vertical and horizontal stirrups is more effective with the increase in span to depth ratio. Hence, curved beams with smaller cross-sectional area sections can be preferred compared with larger cross-sectional area sections for the introduction of spiral vertical stirrups and horizontal stirrups.

V. CONCLUDING REMARKS

Based on the experimental results, the following concluding remarks can be made:

—The ultimate load-carrying capacity of the RC curved beam increases approximately by 13% and 16% for the varying depth of 200 mm and 150 mm, with the introduction of spiral vertical stirrups and horizontal stirrups. Spiral vertical stirrups offer resistance against flexural loading by twisting and bending. Horizontal stirrups offer resistance against applied axial loading. Also, both spiral vertical stirrups and horizontal stirrups resist the shear developed during flexural loading.

—A decrease in depth of beam improves the performance of RC curved beams with the introduction of additional vertical and horizontal stirrups. The introduction of additional stirrups is effective in a smaller section beam (150 mm × 150 mm) compared to a larger section beam (150 mm × 200 mm).

—From the overall study, it is evident that the performance of the RC curved beam is increased by the introduction of spiral and horizontal stirrups as transverse shear reinforcement for smaller section beams. Also, the efficient section for reinforced curved beams can be developed with the introduction of spiral and horizontal stirrups without increasing the width of the beam.

VI. FUTURE SCOPE

The present study can be further extended as follows:

An analytical and numerical investigation can be carried out to study the effect of transverse shear reinforcement by varying various parameters such as boundary condition, the radius of curvature, width of the beam, length of the mechanical properties of steel and concrete. Torsional load-deformation characteristics of curved RC beams can be analyzed experimentally and analytically to determine the out of plane bending behavior of beams.

Conflict of Interest. There is no conflict of interest between authors.

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