Reinforced Concrete Curved Beams in Literature

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Abstract: The current paper presents a review of some previous experimental and theoretical studies concerning reinforced concrete (RC) curved or ring beams, behavior and strength. Due to curvature, it is necessary to include torsional effects in the analysis and design. The most effective parameters worth to be reviewed are; ring diameter, number of supports, width of beam, concrete compressive strength, and width of bearing plate. There are different analysis methods to estimate the load capacity and behavior in addition to finite element analysis. From the previous studies it was concluded that increasing ring diameter decreases the load capacity, while increasing number of supports, width of beam, concrete compressive strength, and width of bearing plate increases the load capacity due to the increase in beam section or its properties. RC ring beams fail in flexure, while the deep ring beams fail in shear in a manner similar to straight beams. Plastic analysis and strut and tie model (STM) are useful tools to analyze curved or ring deep beams effectively. Furthermore, the three-dimensional, nonlinear finite element modelling is ideal for predicting the behavior of RC curved deep beams.

Key words: Reinforced Concrete, Curved, Ring, Deep, Beams, Literature

1. Introduction
It is important to note that in a curved beam, unlike a straight beam, the centroidal axis and the neutral axis are not identical. In addition, stresses from the neutral axis do not vary in a linear manner. In a curved beam, torsional moments happen due to the fact that the applied loads and the reactions do not lie at the main axis along the curved beam [1]. Torsional moments are zero at the mid span between any two sequential supports, in the case of a circular beam with supports that are equally spaced. Maximum values of torsional moments develop at the contraflexure points, rather than in the zones of zero bending moments [2].

Curved beams have been frequently applied in many engineering disciplines such as civil, mechanical, aerospace, etc. Curved beams are thus widely used, in everything from bridge structures, to balconies. In the same way, ring beams have many uses, and are found in domes, circular reservoirs, silos, offshore structures, and many other projects. Deep, rather than shallow, ring beams are commonly used as they are known to have high load resistance. Ring beams mostly act through uniformly distributed loads, for
example to support a load transferred from a dome to the rest of the structure; they are not commonly used to support point loading [3].

Reinforcements are a key feature in the improvement of curved and ring beams – RC is mostly used for deep ring beams as it is easier to construct, although steel beams have also been applied to some curved constructions. And yet, the impact of lateral loading on the mode of failure, cracking pattern, and ultimate load of RC ring beams has been clearly understood [4].

In addition to the curvature, the depth of the beam section also plays an important role. The ACI 318M-19 Code defines deep beams as [5]: "the structural members that are supported on a face and loaded on the opposite face such that shear stresses can develop between the supports and loads. That satisfies (a) or (b): (a) Single forces lie in a distance 2h from support face; and (b) Clear span is not more than the four times the depth of the member h”.

One of the most effective methods for analyzing RC deep beams in which D regions exist are strut and tie modeling (STM) [6-15]. The STM method is simply to impose a truss that connects the loading points with the supporting points through compressive members (struts) that are connected with tensile members (ties) by nodes [16-25].

Another key method is plastic analysis, in which ultimate load resistance and plastic hinge is seen as a main design consideration. A plastic hinge is a compromised point at which shifts and rotations can occur, due to bending in a structural member such as a joint, support or beam. Different types of moments appear in ring or curved beams; therefore, plastic analysis can be effectively used in these types of structures.

The finite element method (FEM) and the finite difference method (FDM) are also commonly employed theoretical methods for the analysis of beams and other engineering structures. However, both FEM and FDM often require costly corrections to achieve accurate results, as they typically use low-order schemes.

Despite the abundance of research works that deal with curved or ring beams, there is a clear lack of research works on RC curved or ring deep beams. The most important of the few research works that are available will be summarized below.

2. Previous research works
2.1 Experimental investigations

In 1977, Badawy et al. [26] investigated the combined effect of bending, torsion, and shear on RC beams using plastic analysis with two yield criteria. Fifteen beams in total were tested, seven of which were straight and eight of which were curved beams with 2.21 m radius and 75 degrees subtended angle as shown in Figure 1. Every curved specimen was tested under 1-concentrated force. Four curved specimens were reinforced conventionally but were tested under varied end conditions; both the end conditions and the transverse reinforcement were varied between each of the curved specimens. The straight specimens were reinforced in the same way as the curved specimens and were tested under varied combinations of torsion, bending, and shear; this was done in order to investigate where the two yield criteria intersected with bending, torsion, and shear axes. The straight beams were also checked to validate the yield criteria, when applied to the curved beams.

Badawy et al.’s plastic analysis was founded on an initial yield study that defined the beam’s behavior under the combined action of torsion and bending only, i.e. shear is neglected in the first criterion. The analysis was then modified to contain the shear effect, and the initial results were compared with the results including shear. The authors were then able to contain the shear effect in their analysis of reinforced and pre-stressed concrete. Badawy et al. studied the crack patterns, the misshaping of the beams and the reinforcement strains in curved beams in order the find plastic hinge moments, and thus analyze modes of failure. The types of plastic hinge – either torsion-shear hinges, flexural hinges, or bending-torsion-shear hinges – were also monitored. The experimental test results were compared with the results predicated by plastic theory, through which the study concluded that:

1- A plastic analysis approach can be used in the study of RC curved beams.
An analysis using the first criterion (bending and torsion only) presents an acceptable ultimate load predication, failure mode and the interior forces. However, an analysis using the second criterion (including shear) establishes a lower threshold for the internal forces and the ultimate load. For these two surfaces, the dimensionless equations are:

\[ \frac{m^2 + t^2}{(1 - v^2)} = 1, \quad \text{for the 1st yield criterion} \]
\[ \frac{m^2 + t^2}{(1 - v)} = 1, \quad \text{for the 2nd yield criterion} \]

Where \( m = \frac{M}{M_p} \), \( t = \frac{T}{T_p} \), \( v = \frac{V}{V_p} \); \( M \), \( T \) and \( V \) are the bending moment, torsion and shear respectively; and \( M_p, T_p \) and \( V_p \) are the related cross-section plastic capacities in pure bending, torsion, and shear.

Two types of internal forces redistribution take place in a curved beam; one because of cracking and the other because of the formation of plastic hinge.

The failure modes effect is precisely predicted using plastic analysis.

In 1978, Hsu et al. [27] studied the redistribution of torsional and flexural forces in RC curved beams after cracking has occurred. This study was done to produce more suitable designs based on a beam post-cracking. Seven curved beams were tested, each with 2.74 m radius and 90 degrees subtended angle. All seven beams were fixed at both ends and were tested using a concentrated load at mid span. The first and second beams were analyzed using conventional design methods on uncracked structures; elastic theory was used to design reinforcements under the ACI Building Code (1971). The third and fourth beams were also designed based on elastic theory for uncracked sections, yet were only modeled for a portion of the maximum torsion moment. The 5th and 6th beams were designed using the calculations from the elastic method according to cracked sections. The 7th beam was designed as a uniform beam with stirrups and longitudinal bars. For cracked sections, the torsional rigidity was found through the post-cracking torsional rigidity, which was derived from the analogy of the space truss by Hsu (1972). Through testing modes of failure and internal forces on the seven beams, Hsu et al. observed that torsional and flexural moments were greatly redistributed after cracking. Results showed that early yielding was seen at the supports for beams that were modeled using the traditional design methods, based on "Building Code Requirements for RC (ACI 318-71)" and elastic analysis, as these designs were based on uncracked sections. As a result,
Hsu et al. suggested that cracking should be taken into account in beam design, and beam design must be according to cracked sections.

In 1981, Abul Mansur and Rangan [28] studied three varied design methods for RC curved (horizontally) beams:

1- A method of collapse load suggested by Badawy et al., 1977 [26].
2- The classic elastic method according to uncracked sections.
3- A method of limit design suggested by the authors themselves.

These three design points were used in order to investigate the strength, mode of failure, and effect of steel reinforcements on curved beams. Two further conditions were taken into account in Abul Mansur and Rangan’s limit design method to design a statically indeterminate system. The 1st additional condition was presented through supposing an ultimate design torsional moment equal to $0.33 \times \frac{x^3}{y^4}$ in (N.mm) at critical sections, where $x_1$ and $y_1$ are the smaller and the larger dimensions, respectively, of a rectangular section (mm), and $f_c$ is the concrete compressive strength (MPa). The 2nd additional condition was provided through supposing an inflection point position (at which the bending moment is zero) based on elastic analysis.

Figure 2 shows the results of tests on the beams designed using the three methods outlined above. Each beam had 2.45 m radius and 90 degrees subtended angle; a vertical point loading test was used, and the beams were static and fixed to supports. Results of the study indicated that:

1- Two key moments lead to internal forces redistribution in a RC curved beam. The first stage is after cracking, and the second stage is after the plastic hinges formation (as concluded by Badawy et al. [26]).
2- Although all three methods produced satisfactory results of RC concrete beams, Badawy et al.’s method was the least effective in terms of steel usage. The beam samples designed using a collapse load method needed a higher volume of steel (primarily steel rings) than the other two methods.

In 2014, Zhao et al. [29] studied experimentally the behavior of RC ring beams connected to concrete-filled steel tube (CFST) columns. Displacements, stresses, failure patterns, and energy dissipation capabilities of three samples specimens were analyzed through testing using low cyclic loading conditions. The effect of difference ring beam dimensions on load capacity and mode of failure was also studied. The experimental results were compared against the results from numerical simulation also in order to validate the method. From investigating the stress distributions of joints with and without the ring beam, Zhao et al. concluded that:
1- The joint typical failure pattern with the ring beam is the development of plastic hinges. This failure took place in the RC frame beam, but there was no evidence of this mode of failure between the ring beam and the column.

2- The joint’s ‘spindle shaped’ hysteretic curves do not show evidence of declining strength and stiffness during the loading test, and thus exhibit good behavior. The ratio of displacement ductility is over three, and the coefficient of equivalent viscous damping is 0.172 and 0.201.

3- The dimension of the ring beam is an important factor in the load capacity and failure resistance of the joint connection. The displacement ductility ratio, energy dissipation capacity, and ultimate load capacity of the joint are all improved by increasing the ring beam dimension.

In 2016, Wei, Yiyi and Wanqi [30] used an experimental method to analyze a new type of RC ring beam, using joints between concrete filled steel tube (CFST) columns. Wei, Yiyi and Wanqi investigated the curved beam and column behavior using bidirectional cyclic loading tests. Four specimens of CFST columns were tested and the results suggested that:

1- The ring beams’ internal forces are influenced by the interaction between the ring beam and the CFST column when an external load is imposed.

2- When affected by cyclic loading tests, cracks developed near the proximity of the ring, which suggests that the force system in ring beam is multi-directional.

3- Multi-directional forces, such as bending, axial load, shear, and torsion should be taken into account in the design of RC ring beams. When designed in this way, joints between beams and columns are more resistant to seismic loads, and have improved ductility.

2.2 Numerical and theoretical analysis of curved and ring beams

In 2002, Al-Temeemi [31] used the finite elements method in order to study the behavior of RC horizontally curved beams on elastic foundations, taking material nonlinearity into account for concrete and steel. The concrete was modeled using a 20-node isoperimetric brick element with 60 degrees of freedom, and axial members within the brick elements were used in order to model the reinforcing bars. Normal reactions (signified by Winkler, Kondner, and Polynomial models) and horizontal subgrade reactions (signified by the Winkler model) are used to model soil. The finite element modeling proposed by Al-Temeemi showed a high level of agreement with the available experimental and numerical theoretical results. The effect of some significant parameters on the overall behavior of RC curved beams on elastic foundations was analysed: such as; radius to span-length ratio (R/L), boundary conditions, α1 (the rate of stress release as the crack widens in the beam), α2 (the sudden loss of stress at the moment of cracking in a beam), and the soil type. Al-Temeemi’s results indicated that increasing (R/L) could increase the ultimate load for a curved beam on elastic foundations: when R/L increases from 1 to 5, the ultimate load increment becomes about 40%. The use of shear reinforcement bars was also found to have an important impact on the ultimate load of the curved beams; it was found that the ultimate load decreased by about 51% when the shear reinforcement was removed.

In 2011, Al-Azzawi and Shaker [32] investigated the effect of elastic foundations with compression and friction resistance on the elasticity of deep curved beams. In this study, deep beam Timoshenko’s theory is extended to contain the effect of externally distributed forces and curvature, therefore enabling analysis of curved beams in static conditions. Figure 3 illustrates the complications of deep beams resting on elastic foundations with both compressional and frictional restraints. Al-Azzawi and Shaker used the method of finite difference to model deep curved beams; they compared the results with other approaches for accuracy check. The horizontal subgrade reaction, vertical subgrade reaction, beam thickness to radius ratio, and the beam width were all included in the analysis, to investigate their effect on the bending moments, shear forces, and deflections of the curved beams. Al-Azzawi and Shaker coded the computer program CDBFDA (Curved Deep Beam Finite Difference Analysis Program) fortran-77 for this analysis, and checked the results from the computed method against other exact, experimental and numerical
method studies in order to check their accuracy, with good levels of agreement. The average difference percentages for moments and deflections are 7.3% and 5.3%, respectively, which show the adopted method efficiency for analysis. A parametric study showed that:

1. Increasing the thickness to radius ratio from 0.1 to 1 decreases the free curved beam maximum deflection under 4 concentrated forces by about 63.5%.
2. Increasing free curved beam width from 762 to 3048 mm decreases the maximum deflection for the curved beam under 4 concentrated forces by about 75%.
3. When the vertical and horizontal subgrade reactions ($K_v$) and ($K_h$) increase, the maximum deflection decreases. The maximum deflection will almost linearly decrease as the horizontal subgrade reactions increases. It was seen that the free curved beam horizontal and vertical subgrade reactions increase from $0.2 \times 10^{-3}$ kN/mm$^3$ to $0.1 \times 10^{-2}$ kN/mm$^3$ for the horizontal and from $0.135 \times 10^{-3}$ kN/mm$^3$ to $0.6 \times 10^{-3}$ kN/mm$^3$ for the vertical, the maximum deflection decreases by 65.3% and 7.184%, respectively.

![Figure 3. Curved deep beam of fixed ends under uniform distributed load (q), resting on an elastic foundation, Al-Azzawi and Shaker (2011).][32]

In 2013, Al-Mutairee [33] discussed producing an optimal strength for RC curved beams using a non-uniform layout of longitudinal reinforcements, without increasing the volume of the longitudinal reinforcements. The computer program nonlinear finite element analysis of horizontally curved beam under static load (NFHCBSL) was used to conduct 3D nonlinear finite element analysis; 20-node isoperimetric brick elements were incorporated to model the elements of concrete, while reinforcing bars were represented as axial members embedded inside the elements of concrete. The study indicated that the use of non-uniform distribution of longitudinal reinforcement is efficient in fixed-ends RC horizontally curved beams. The resistance to ultimate load, and the strength of the beam was improved, which becomes increasingly important as the horizontal curvature angle ($\theta$) also increased.

In 2010, Ali A.Y. [34] investigated the behavior of RC, deep, curved beams, pre and post-cracking when loaded transversely up to the ultimate load. The beams were designed using a three-dimensional nonlinear finite element model. The concrete was modeled using the ANSYS program, using a 20-node isoperimetric brick element with 60 degrees of freedom and the concrete was reinforced using bars, designed as axial members embedded inside the brick element of concrete. A perfect bond between the reinforcing bars and concrete was assumed. Numerical and material parameters were changed in order to analyze their effect on the beams' predicted load-deflection curve and ultimate load capacity. Ali A. Y. studied numerical parameters such as the boundary conditions, central subtended angle, amount of transverse reinforcement, and the use of additional longitudinal bars (i.e., horizontal shear reinforcement). These were investigated on RC curved beams with different shear length to effective depth ratios (a/d), resulting in the conclusion that decreasing the central subtended angle causes an increase in beams' ultimate load capacity.
In 2014, Al Qaicy et al. [4] used nonlinear finite element analysis (NLFEA) for analyzing three specimens of concrete ring beams that were each supported on four equally spaced columns. The columns were each 3 m in height (h), measured from the base of column to the base of the ring beam. The beams were similar, the only differences being the depth of the beam (500, 1000 and 2000 mm), and the percentage of the main reinforcement. They studied the ultimate load strength, mode of failure, patterns of cracks, and deformed shape at point of failure. Al Qaicy et al.’s NLFEA results indicated that the modes of failure for the ring beams are conditional on the depth/span ratio (the span/depth ratio being the same as in straight beams in this study). They concluded that the shallower ring beams failed in flexure, while the deep ring beams failed in shear, as also happens in straight RC beams. The tension-stiffening value ranged from 0.002 to 0.003.

In 2020, Abdul-Razzaq et al. [35] studied the most effective two-span top-loaded deep ring beam parameters on twenty specimens using STM. Five groups of beams were used – A, B, C, D and E – with 4 specimens in each group (see Table 1). Group A included 4 specimens of differing ring diameter; 1 m, 1.25 m, 1.5 m, and 1.75 m. Group B included 4 specimens with varying numbers of supports; 3, 4, 5, and 6. Group C included 4 specimens that had different ring beam widths; 0.1 m, 0.125 m, 0.15 m, and 0.175 m. Group D included 4 specimens of varying concrete compressive strengths; 25 MPa, 31 MPa, 38 MPa, and 44 MPa. Group E included 4 specimens with different bearing plate widths; 100 mm, 125 mm, 150 mm, and 175 mm.

The main conclusions were:

1- Increasing a/h ratio by increasing the ring beam diameter causes a decrease in load capacity. More specifically, increasing ring diameter by about 25-75% decreases ring load capacity by about 14-36%. This decrease happens because increasing the ratio of arc shear to overall height, and increasing the ratio of central horizontal to vertical angle $\theta h/\theta v$, increases the length of the compressive struts and decreases the strut-tie angle.

2- Increasing the number of supports increases the ring beams’ resistance to loading. More specifically, increasing the number of supports by 33.33–100%, increases ring load capacity by 62.04–188.86%. This increase occurs because increasing the number of inclined struts and increasing the strut–tie angle leads to a decrease in the strut length, decreasing the ratio of arc shear to overall height, which decreases the horizontal central to vertical angle ratio $\theta h/\theta v$.

3- Ring load capacity can be directly affected by increasing beam width. In more detail, increasing beam width by about 25–75% increases load capacity by 25–75%. This is due to the direct relationship between the beam width and the sectional areas of the strut, tie, and the faces of the related nodes.

4- Increasing the concrete compressive strength increases the strength of the struts and the related nodes, which correspondingly has a direct impact on the load capacity. That is why the ring load capacity increases by 24–76% when the f’c increases by 24–76%.

5- The load capacity of a ring beam increases when the width of the bearing plate increase, as nodes and struts are strengthened. Consequently, increasing the bearing plate width by 25–75% leads to an increase in the load capacity by 5.3–15.85%.


3. Concluding remarks

1- RC curved beams can be analyzed using a plastic approach, although this is dependent on the formation of plastic hinges, and the conditions of the sections in which they are formed.

2- The ultimate load, internal forces and mode of failure for a curved beam can be predicted using the first criterion. The second criterion can be used, which establishes a lower threshold for internal forces and ultimate load of curved and ring beams. Further investigations, and particularly experimental data, are needed in order to verify yield criteria on a range of section and material properties. Studies suggest that plastic theory is effective in predicting the ways in which end conditions affect ultimate loads and modes of failure in curved beams.

3- The strut and tie model (STM) is effective for the analysis of RC deep members containing D regions.

4- RC ring beams have a high level of plasticity and stretch and are suitable for seismic resistance applications.

5- The three-dimensional, nonlinear finite element analysis model (NLFEA) is ideal for predicting the behavior of RC curved deep beams.

6- The ultimate load is significantly affected by varying the central subtended angle (curvature) of curved beams, while the length of those beams is kept constant. Decreasing the central angle leads to increase in curved beams’ resistance to ultimate load.

7- Generally, the ultimate shear capacity of ring deep beams increases with decreasing a/d ratio.

8- It has been found that a flexure type failure occurs in ring beams, whereas a failure due to shear can be found in deep ring beams, which is the same type of failure found in straight RC beams.

### Table 1. All specimens, Abdul-Razzaq et al. (2020). [35]

| Group | Specimen | Total depth (h) mm | Arc Shear Span (a) mm | Ring diameter (De) mm | Number of support | Width of specimen (bw) mm | Compressive Strength (f’c) MPa | Width of Bearing Plate (Bp) mm | Parameter |
|-------|----------|-------------------|----------------------|----------------------|------------------|-------------------------|-----------------------------|-------------------------------|-----------|
| A     | RD1      | 500               | 523.33               | 1000                 | 3                | 150                     | 31                          | 150                           | Ring diameter             |
|       | RD2      | 500               | 654.17               | 1250                 | 3                | 150                     | 31                          | 150                           |                       |
|       | RD3      | 500               | 785                  | 1500                 | 3                | 150                     | 31                          | 150                           |                       |
|       | RD4      | 500               | 915.83               | 1750                 | 3                | 150                     | 31                          | 150                           |                       |
| B     | RD5      | 500               | 654.17               | 1250                 | 3                | 150                     | 31                          | 150                           | Number of support         |
|       | RD6      | 500               | 490.63               | 1250                 | 4                | 150                     | 31                          | 150                           |                       |
|       | RD7      | 500               | 392.5                | 1250                 | 5                | 150                     | 31                          | 150                           |                       |
|       | RD8      | 500               | 327.08               | 1250                 | 6                | 150                     | 31                          | 150                           |                       |
| C     | RD9      | 500               | 654.17               | 1250                 | 3                | 100                     | 31                          | 150                           | Width of specimen          |
|       | RD10     | 500               | 654.17               | 1250                 | 3                | 125                     | 31                          | 150                           |                       |
|       | RD11     | 500               | 654.17               | 1250                 | 3                | 150                     | 31                          | 150                           |                       |
|       | RD12     | 500               | 654.17               | 1250                 | 3                | 175                     | 31                          | 150                           |                       |
| D     | RD13     | 500               | 654.17               | 1250                 | 3                | 150                     | 25                          | 150                           | Compressive Strength      |
|       | RD14     | 500               | 654.17               | 1250                 | 3                | 150                     | 38                          | 150                           |                       |
|       | RD15     | 500               | 654.17               | 1250                 | 3                | 150                     | 44                          | 150                           |                       |
|       | RD16     | 500               | 654.17               | 1250                 | 3                | 150                     | 31                          | 100                           |                       |
| E     | RD17     | 500               | 654.17               | 1250                 | 3                | 150                     | 31                          | 125                           | Width of Bearing Plate    |
|       | RD18     | 500               | 654.17               | 1250                 | 3                | 150                     | 31                          | 150                           |                       |
|       | RD19     | 500               | 654.17               | 1250                 | 3                | 150                     | 31                          | 150                           |                       |
|       | RD20     | 500               | 654.17               | 1250                 | 3                | 150                     | 31                          | 175                           |                       |
9- The deep ring beam ultimate capacity of the decreases when the diameter of the deep ring beam is increased.
10- The deep ring beam ultimate capacity of the effectively also decreases when load is transferred from near a support to the mid span.

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