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Reinforced Concrete Semi-Circular Deep Beams - Finite Element Investigation

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ABSTRACT

This paper represents a parametric study utilizing finite element analysis for twenty-five reinforced concrete semi-circular deep beams. The parameters that were taken into consideration in the current work are radius, height, width, concrete compressive strength and number of supports. It is found that decreasing radius of beam by 16-66% leads to decrease the midspan positive moment, support negative moment, torsional moment and midspan deflection by about 0.3-20%, 2.4-25%, 2-24% and 29-85%, respectively, while the load capacity increases by about 23-158%. The midspan positive moment, support negative moment, torsional moment and load capacity increase by about 20-682%, 20-81%, 20-81% and 21-84%, respectively, whereas midspan deflection decreases by 7-17% when the beam height increases by about 16-66%. The positive moment, negative moment, torsional moment and load capacity increases by about 43-197%, 40-185%, 29-187% and 46-214%, respectively, whereas deflection decreases by about 1.4-3.3% when the beam width increases by about 16-66%. The positive moment, negative moment, torsional moment and load capacity increases by about 10-84%, 9-77%, 9-79% and 11-92%, respectively, whereas deflection decreases by about 0.1-0.5% when the compressive strength increases by 20-220%. Finally, it is found that the positive moment increases by about 36-47% when number of supports increased by 33-66%, while the negative moment increases by about 16-31% when number of supports decreases by 14-29%, whereas the torsional moments and deflection decreases by about 6-55% and 37-84%, respectively when number of supports increases by 33-133%, while load capacity increases by 156-969% when number of supports increases by 33-133%.

1. Introduction

Currently, semicircular deep beams are extensively utilized in the constructing of semicircular shells, foundation, and base reservoir or to achieve some aesthetic employments in addition to their normal use in curved constructions [1]. Semicircular reinforced concrete deep beams, when are subjected to surface loads, transverse to their planes, they will be submitted to shear, bending and torsion. Thence, a distinctive feature of the analysis and design is necessary to contain combined influence.

Reinforced concrete semicircular deep beams are widely supported by more than two supports. The ACI 318M-14 Code acquaints deep beams as [2]: "the beams that are supported on a face and loaded on the opposite face as shear stresses can form between the loads and supports. That must satisfy (1) or (2): (1) concentrated loads occurred in a displacement 2h from face of support; and (2) Clear span is not more than four times the beam depth h". As

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though, most of the present investigations to explain the structural behavior and strength of deep beams of structures have cared on single-span deep beams [3-6] and continuous deep beams [7-11], but not cared on semicircular deep beams.

Finite element is so permitted tool for analyzing and designing reinforced concrete structures [12-18]. The semicircular deep beams are so common in structural engineering, whereas lack of such investigations on semicircular deep beams is obvious. That is why this paper showed analytical investigation for twenty-five reinforced normal concrete semicircular deep beams in order to achieve the effects of beam radius, beam height, beam width, concrete compressive strength and number of supports on positive bending moments, negative bending moments, torsional moments, midspan deflection, load capacity, and failure location.

2. Finite element model

The methodology includes using the ETABS software to investigate the parametric effect on a semicircular deep beam. The whole project is broken down into the steps below.

2.1 Modelling

The use of three-dimensional (3D) finite element (FE) analysis to predict the behavior of structural elements has become increasingly popular. The models are created utilizing ETABS 2018 software. The beams are designed according to ACI 318-14 utilizing the maximum capacity of load. The vertical slice mesh has about 80-180 elements along the semicircular and was chosen based on convergence studies to find the best mesh for a relatively accurate solution with minimal computational time. In the current study, steel was assumed to behave as an elastic perfectly plastic material in both tension and compression. The results were obtained and evaluated after analysis.

2.2 Reinforced Concrete Semi-Circular Deep Beam Study Cases

A total of twenty-five reinforced concrete semicircular deep beams are designed. They are divided into five groups; A, B, C, D and E. Each group includes five specimens as shown in Table 1. Group A includes five specimens that have various values of central radius, more specifically, 6000 mm, 5000 mm, 4000 mm, 3000 mm, and 2000 mm. Group B includes five specimens that have various heights; 2400 mm, 2800 mm, 3200 mm, 3600 mm and 4000 mm. Group C includes five specimens that have various semicircular deep beam width values; 300 mm, 450 mm, 600 mm, 750 mm and 900 mm. Group D includes five specimens that have various values of concrete compressive strength; 25 MPa, 30 MPa, 40 MPa 60 MPa and 80MPa. Finally, group E includes five specimens with various number of supports; 3, 4, 5, 6, and 7 supports. Figure 1 shows the semicircular deep beam in 3D modeling.

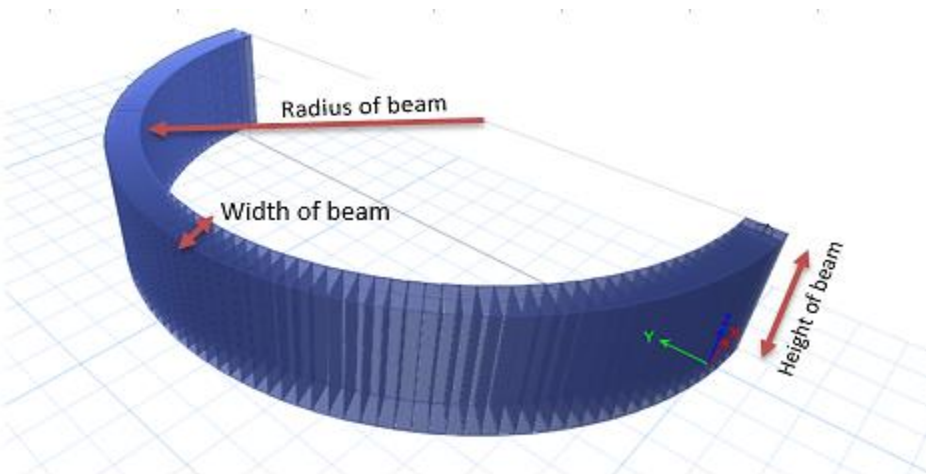

Figure 1. Semi-Circular deep beam

Table 1. Detailed of all specimens

No.	Group	Parameter		Radius (mm)	Height (mm)	Width (mm)	Compressive Strength (MPa)	No. of supports
1	A	dimensions	radius	6000	2400	600	30	3
2				5000	2400	600	30	3
3				4000	2400	600	30	3
4				3000	2400	600	30	3
5				2000	2400	600	30	3
6	B		height	6000	2400	600	30	3
7				6000	2800	600	30	3
8				6000	3200	600	30	3
9				6000	3600	600	30	3
10				6000	4000	600	30	3
11	C		width	6000	2400	450	30	3
12				6000	2400	525	30	3
13				6000	2400	600	30	3
14				6000	2400	675	30	3
15				6000	2400	750	30	3
16	D	Material	Concrete Compressive Strength	6000	2400	600	25	3
17				6000	2400	600	30	3
18				6000	2400	600	40	3
19				6000	2400	600	60	3
20				6000	2400	600	80	3
21	E	Configuration	No. of Supports	6000	2400	600	30	3
22				6000	2400	600	30	4
23				6000	2400	600	30	5
24				6000	2400	600	30	6
25				6000	2400	600	30	7

2.3 Material properties

Semicircular deep beams are constructed of two materials: concrete and steel reinforcement. Each element type in this modeling had been utilized to represent a specified beam's materials. The geometrical properties of the used elements, such as cross-sectional area, are required for the real constants. When the needed material properties based on mechanical tests such as yield stress of main reinforcement (fy), compressive strength (f'c), Poisson`s ratio (ν), yield stress of web reinforcement (fys), modulus of elasticity of steel reinforcement (Es) and modulus of elasticity of concrete (Ec). The material properties of semicircular deep beam are explained in Table 2.

Table 2. Material Properties

Ec (MPa)	Es (MPa)	*f′c* (MPa)	Poisson`s ratio (*ν*)	*fy* (MPa)	*fys* (MPa)
23500	199948	25	0.2	413.7	402
25743		30			
29725.4		40			
36406		60			
42038.1		80			

3. Parametric study

Using ETABS software, the results of maximum positive moments, maximum negative moments, maximum torsional moments, load capacity, maximum midspan deflection, and failure location of all beams are presented in the subsequent paragraphs. Analyzing and design of twenty-five semi-circular deep beams to conduct the parametric study are presented in Table 3.

Table 3. Results of specimens against influential parameters

No.	Group		Parameter	Radius (mm)	Height (mm)	Width (mm)	Compressive Strength (MPa)	No. of supports	Midspan M+ve (kN.m)	Support M-ve (kN.m)	Max. Torsional Moment (kN.m)	Load capacity (kN)	Change In Load Capacity	Deflection (mm)	Change In Deflection
1	A	dimensions	radius	6000	2400	600	30	3	1719	3662	980	2526	-	2.816	-
2				5000	2400	600	30	3	1714	3575	961	3102	+23%	1.99	-29%
3				4000	2400	600	30	3	1680	3444	929	3878	+51%	1.321	-53%
4				3000	2400	600	30	3	1589	3215	870	4966	+97%	0.803	-71%
5				2000	2400	600	30	3	1375	2757	747	6518	+158%	0.436	-85%
6	B		height	6000	2400	600	30	3	1719	3662	980	2526	-	2.816	-
7				6000	2800	600	30	3	2070	4400	1178	3050	+21%	2.621	-7%
8				6000	3200	600	30	3	2422	5141	1377	3576	+42%	2.490	-12%
9				6000	3600	600	30	3	2777	5887	1577	4106	+63%	2.400	-15%
10				6000	4000	600	30	3	3132	6632	1777	4636	+84%	2.335	-17%
11	C		width	6000	2400	450	30	3	905	1985	528	1282	-50%	2.887	+2.5%
12				6000	2400	525	30	3	1290	2779	742	1868	-26%	2.847	+1.1%
13				6000	2400	600	30	3	1719	3662	980	2526	-	2.816	-
14				6000	2400	675	30	3	2188	4624	1239	3248	+28%	2.799	-0.6%
15				6000	2400	750	30	3	2690	5651	1516	4022	+60%	2.793	-0.81%
16	D	Material	Concrete Compressive Strength	6000	2400	600	25	3	1561	3349	895	2274	-10%	2.819	+0.1%
17				6000	2400	600	30	3	1719	3662	980	2526	-	2.816	-
18				6000	2400	600	40	3	1999	4218	1131	2974	+18%	2.813	-0.1%
19				6000	2400	600	60	3	2469	5150	1384	3724	+47%	2.807	-0.32%
20				6000	2400	600	80	3	2866	5938	1598	4358	+73%	2.805	-0.4%
21	E	Configura-tion	No. of Supports	6000	2400	600	30	3	1719	3662	980	2526	-	2.816	-
22				6000	2400	600	30	4	2334	2778	922	6468	+156%	1.773	-37%
23				6000	2400	600	30	5	2521	3497	715	13852	+448%	0.902	-68%
24				6000	2400	600	30	6	2456	3085	565	20555	+714%	0.617	-78%
25				6000	2400	600	30	7	2283	2671	440	27012	+969%	0.462	-84%

3.1 The effect of beam dimensions

This variable is very influential. Five semicircular deep beams that had various magnitudes of radius; 6000 mm, 5000 mm, 4000 mm, 3000 mm and 2000 mm under one midspan concentrated load were investigated. The effect of decreasing the radius of beam by about 16-66% leads to the following findings that took place due to the length of span decrease:

- Maximum positive moments decrease by about 0.3-20%, Figure 2.
- Maximum negative moments decrease by about 2.4-25%, Figure 3.
- Maximum Torsional moments decrease by about 2-24%, Figure 4.
- Load capacity, due to moment reduction, increases by about 23-158%, Figure 5.
- The deflection decreased by about 29-85%, Figure 6.

The mode of failure in all semicircular deep beams occurred between supporting and loading points, which indicates the torsion and shear failure. As an example, Figure 7 shows the failure of semicircular deep beam when radius is 6000 mm.

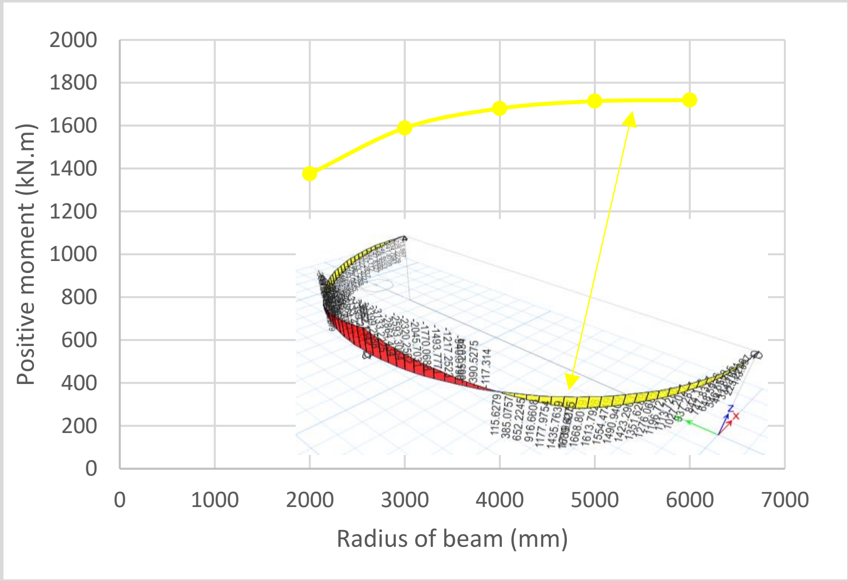

Figure 2. Effect of radius variation on positive moment

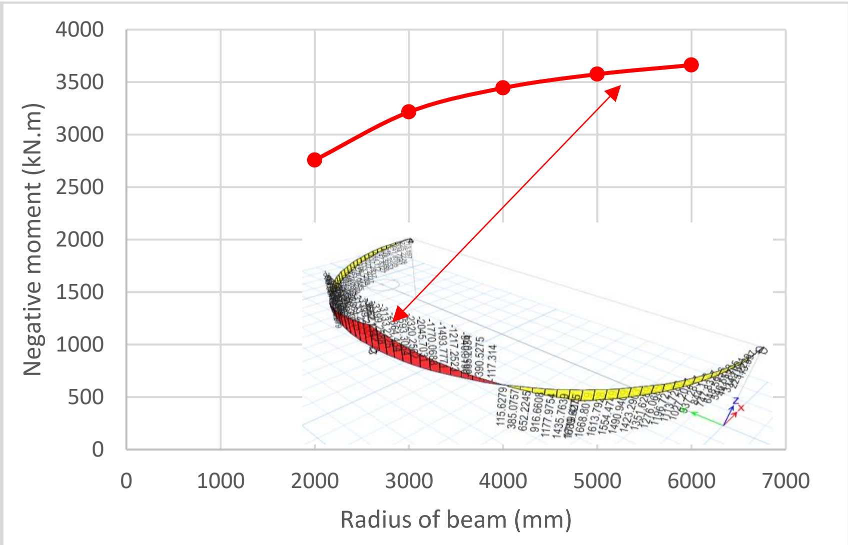

Figure 3. Effect of radius variation on negative moment

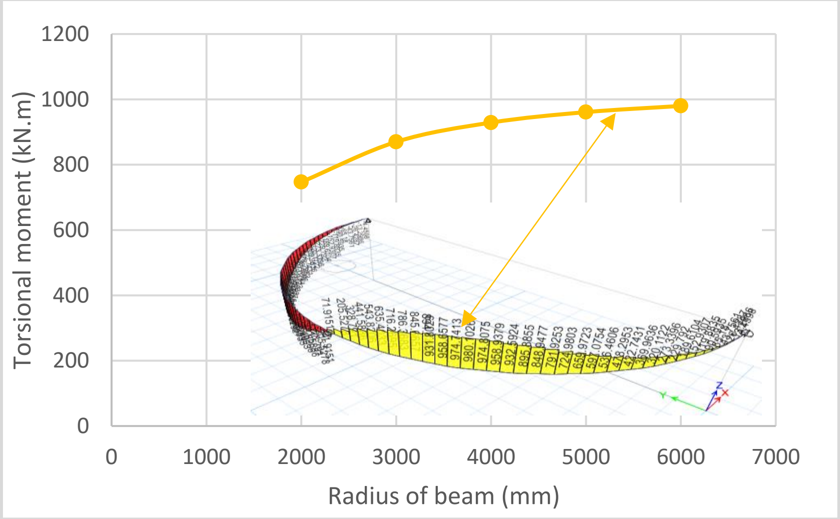

Figure 4. Effect of radius variation on torsional moments

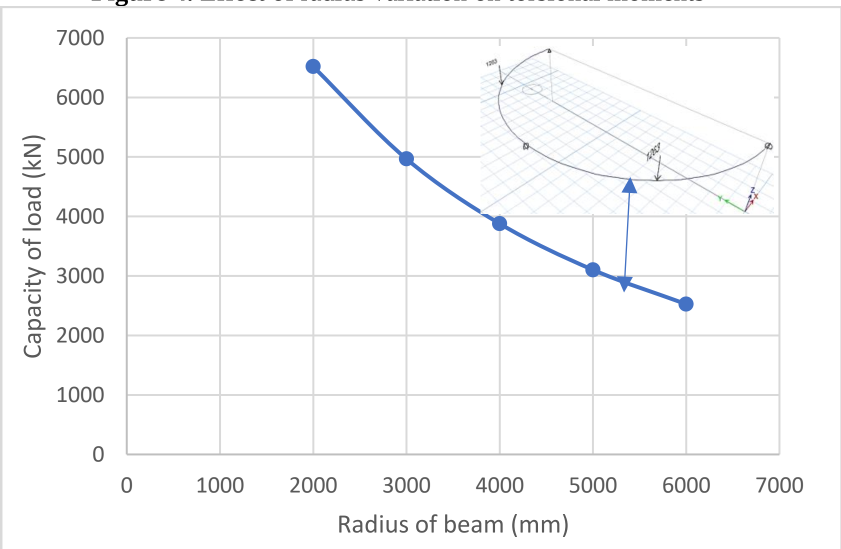

Figure 5. Effect of radius variation on load capacity

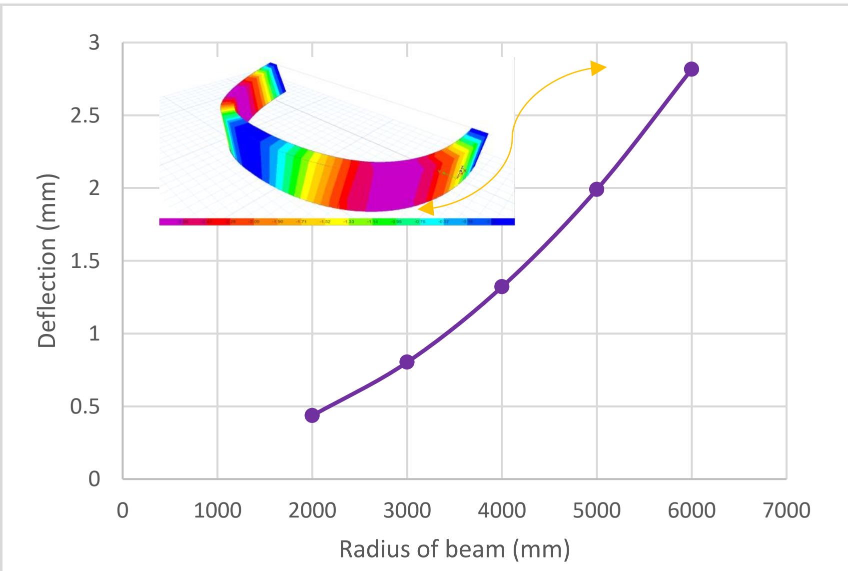

Figure 6. Effect of radius variation on the midspan deflection

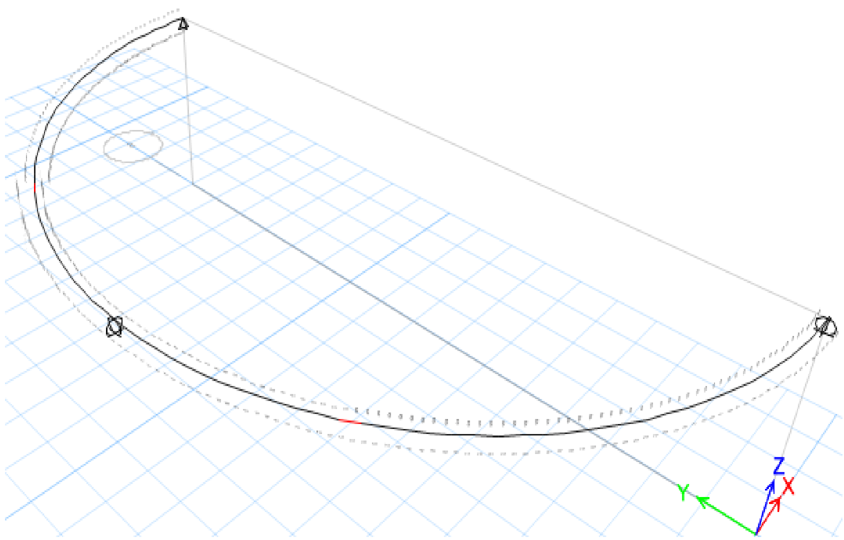

Figure 7. Location of failure in beam with 6000 mm radius

3.1.2 The effect of beam height

To find out the influence of height on the capacity of the one concentrated loaded semicircular deep beam, five semicircular deep beams that had various values of height; 2400 mm, 2800 mm, 3200 mm, 3600 mm, and 4000 mm were modelled. Increasing height by 16-66% leads to increase the concrete sectional area, which means more concrete shear resistance. In more detail:

- The maximum positive moments increase by about 20-82%, Figure 8.
- The maximum negative moments increase by about 20-81%, Figure 9.
- Increasing torsional moments by about 20-81%, Figure 10. That may be happened because of increasing arm of the torsional forces.
- The load capacity increased by about 21-84%, Figure 11.
- Increasing deflection by about 7-17%, Figure 12.

The failure location is lying between supporting and loading zones, which refers to occurrence of torsion and shear failure. Figure 13 shows, as an example, how the failure of semicircular deep beam with a height of 2400 mm occurred between supporting and loading points.

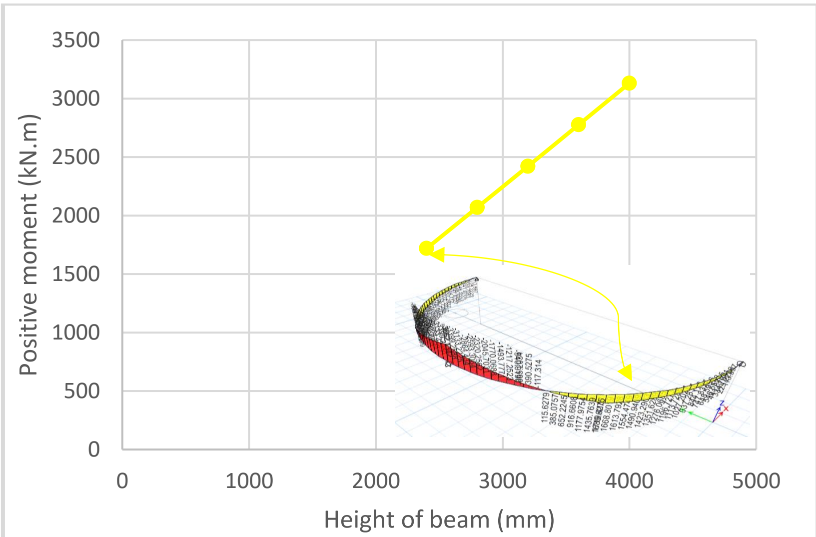

Figure 8. Effect of height variation on positive moment

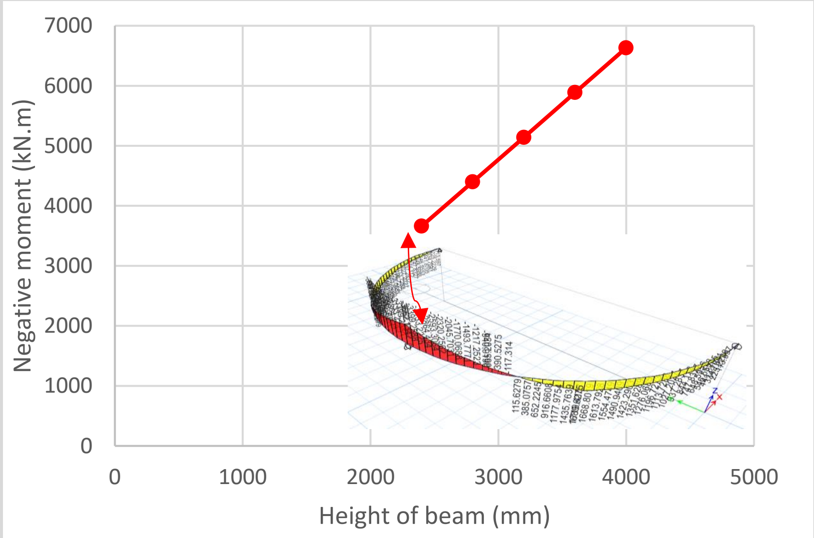

Figure 9. Effect of height variation on negative moment

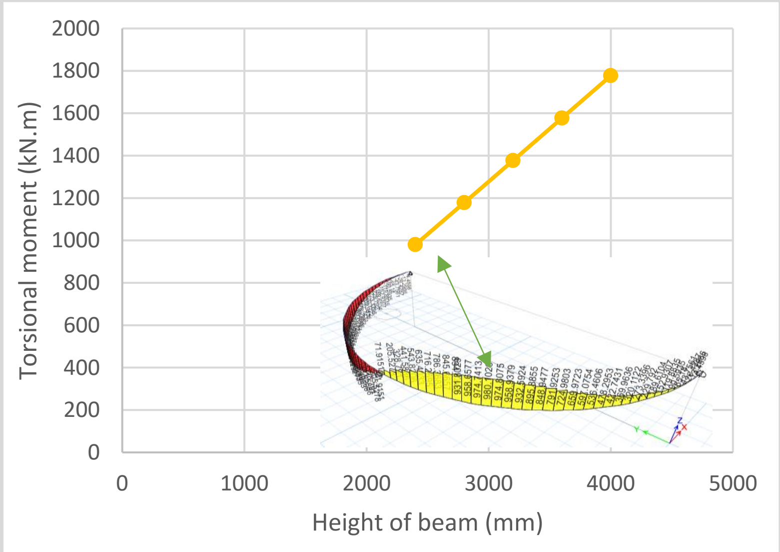

Figure 10. Effect of height variation on the moment of torsion

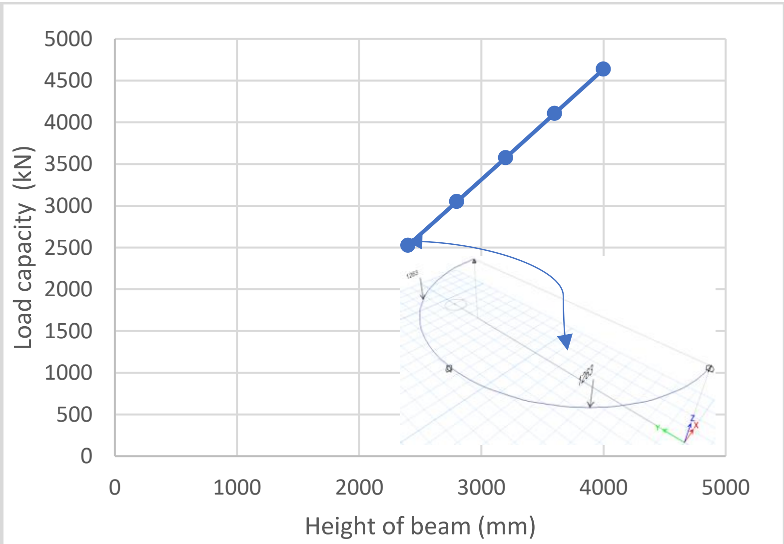

Figure 11. Effect of height variation on load capacity

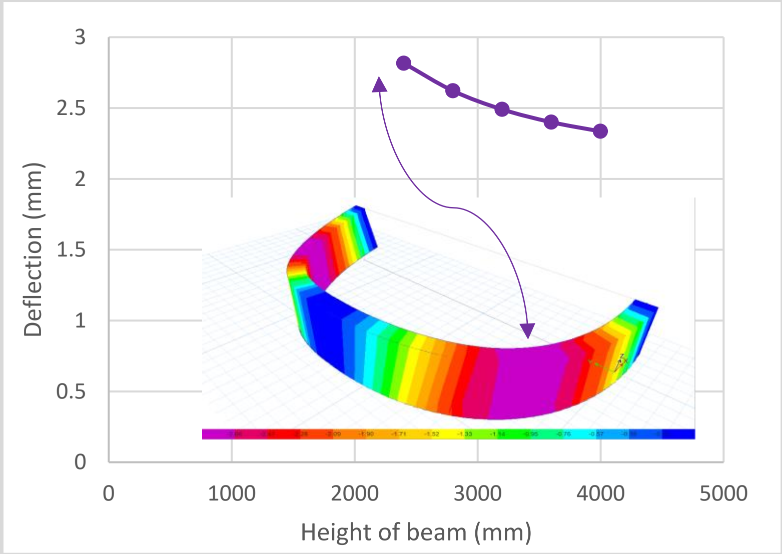

Figure 12. Effect of height variation on the deflection

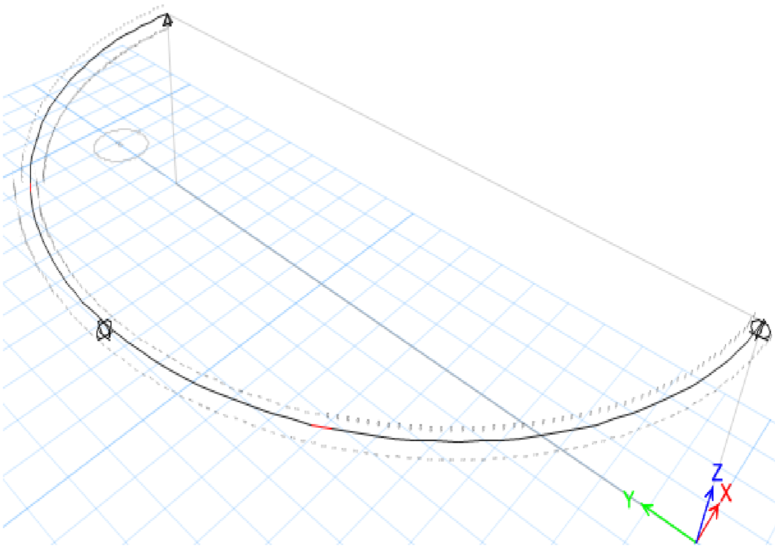

Figure 13. Location of failure of a beam with 2400 mm height

3.1.3 The effect of beam width

Five semicircular deep beams were modeled with various magnitudes of beam width; 450 mm, 525 mm, 600 mm, 675 mm, and 750 mm. Increasing semicircular deep beam width by 16-66%, due to concrete sectional area increase, leads to the following findings:

- The maximum positive moments increase by about 43-197%, Figure 14.
- The maximum negative moments increase by about 40-185%, Figure 15.
- The torsional moments increased by about 29-187%, Figure 16. That happened because of increasing arm of the torsional forces.
- The load capacity increase by about 46-214%, Figure 17.
- The deflection decreased by about 1.4-3.3%, Figure 18.

The failure location is located between supporting and loading zones, which refers to occurrence of torsion and shear failure. As an example, Figure 19 shows how the failure of semicircular deep beam with a width of 600 mm occurred between supporting and loading points.

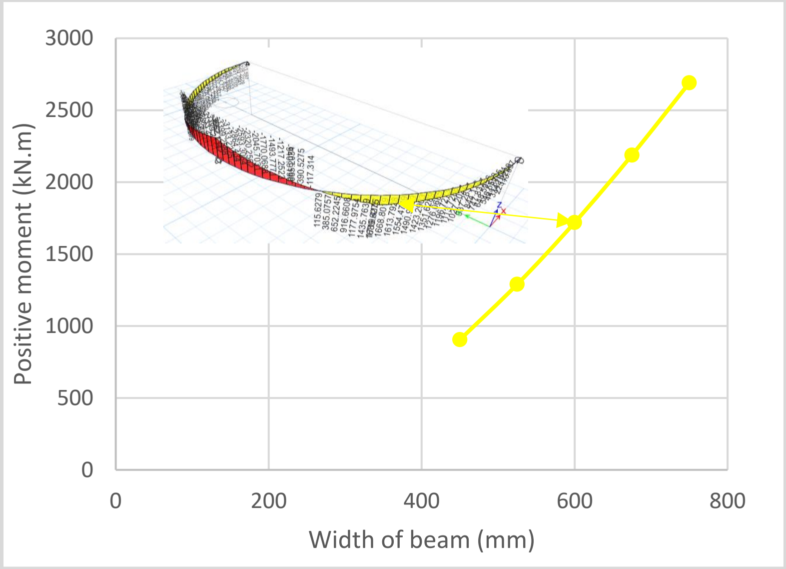

Figure 14. Effect of width variation on positive moment

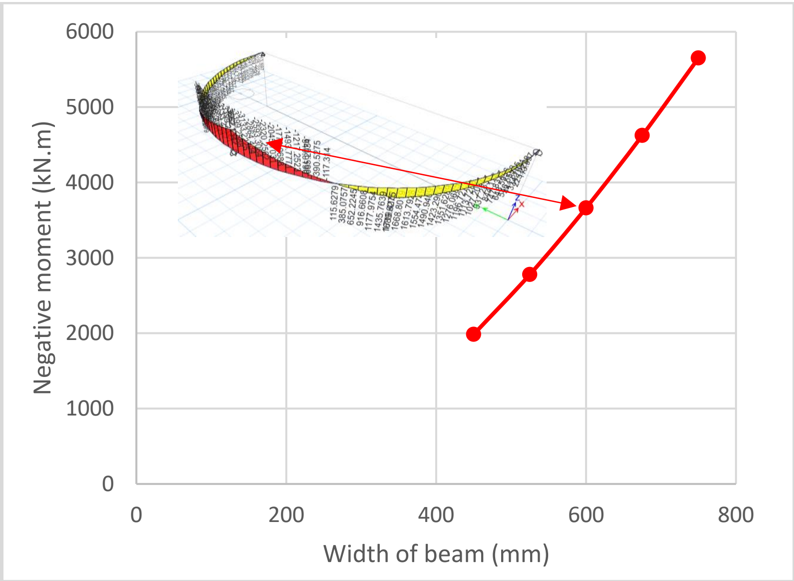

Figure 15. Effect of width variation on negative moment

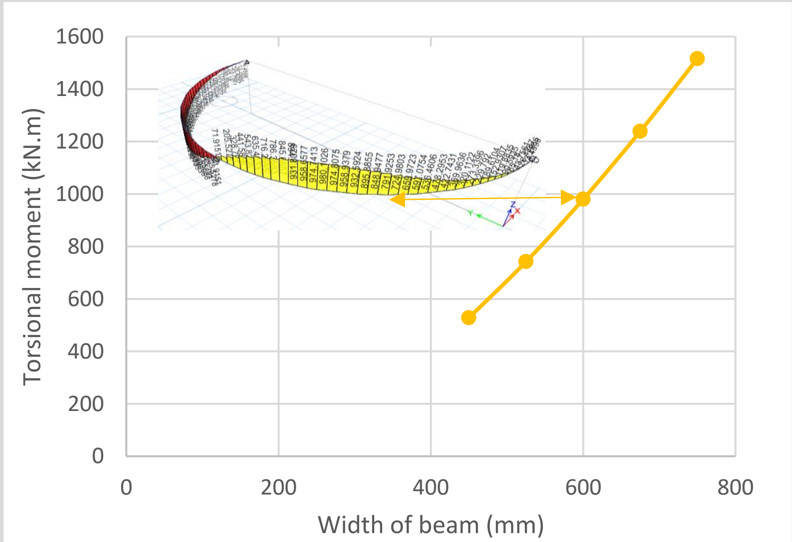

Figure 16. Effect of width variation on the torsional moments

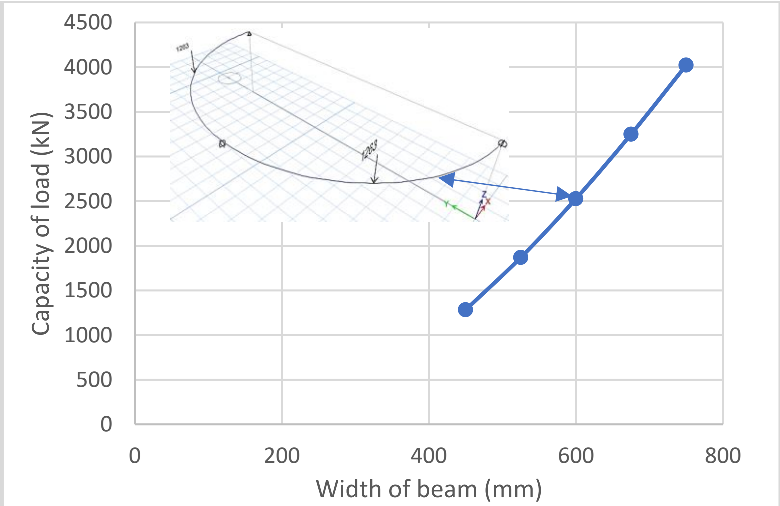

Figure 17. Effect of width variation on load capacity

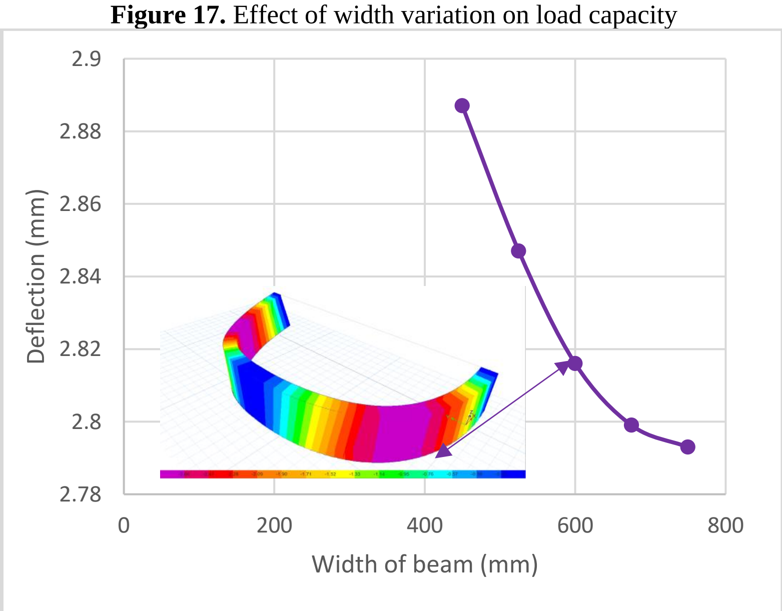

Figure 18. Effect of width variation on the deflection

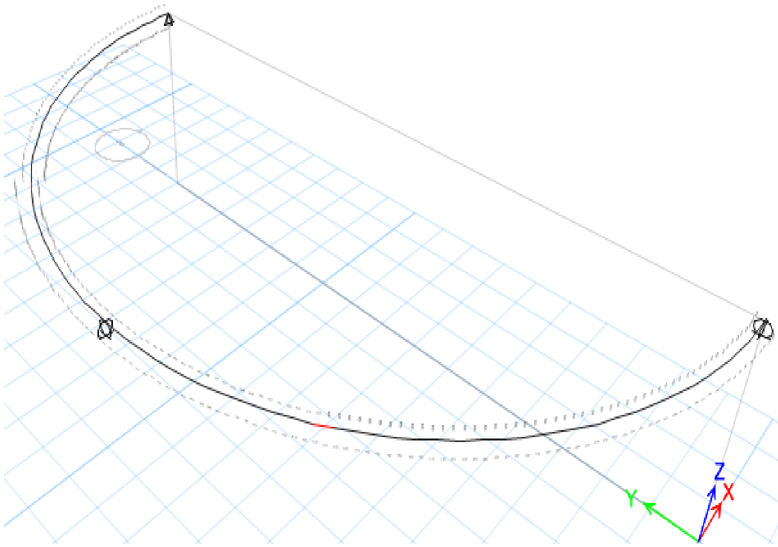

Figure 19. Location of failure in a 600 mm width beam

3.2 The effect of concrete compressive strength

Five semi-circular deep beams that had various magnitudes of compressive strength; 25 MPa, 30 MPa, 40 MPa, 60 MPa and 80 MPa under one concentrated load at mid span were investigated. The increase in the concrete compressive strength by 20-220% causes an increase in the ability of the beam section to resist both compressive and shear stresses. That leads to the following findings:

- Maximum positive moments increase by about 10-84%, Figure 20.
- Maximum negative moments increase by about 9-77%, Figure 21,
- Maximum Torsional moments increase by about 9-79%, Figure 22.
- Load capacity increase by about 11-92%, Figure 23.
- Midspan deflection decrease by about 0.1-0.5%, Figure 24.

The mode of failure in all semi-circular deep beams occurred between supporting and loading points, which indicates the torsion and shear failure. As an example, Figure 25 shows the failure of semi-circular deep beam when compressive strength is 30 MPa.

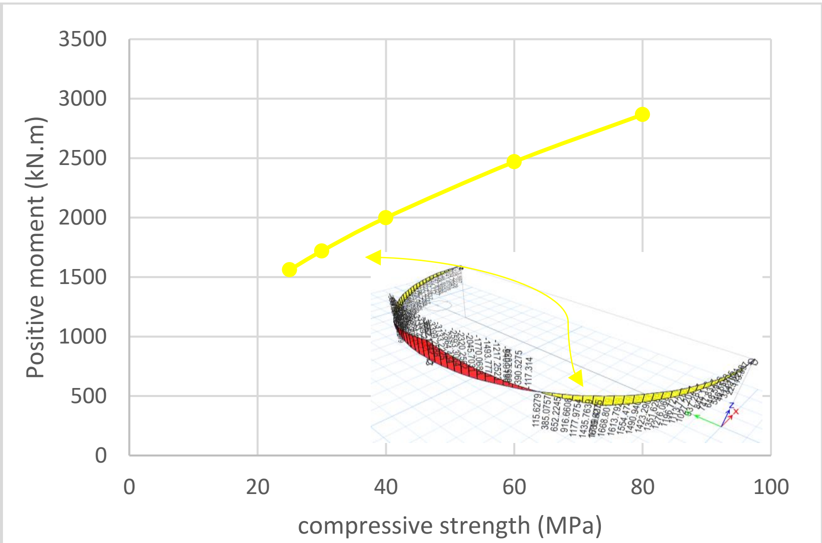

Figure 20. Effect of compressive strength variation on positive moment

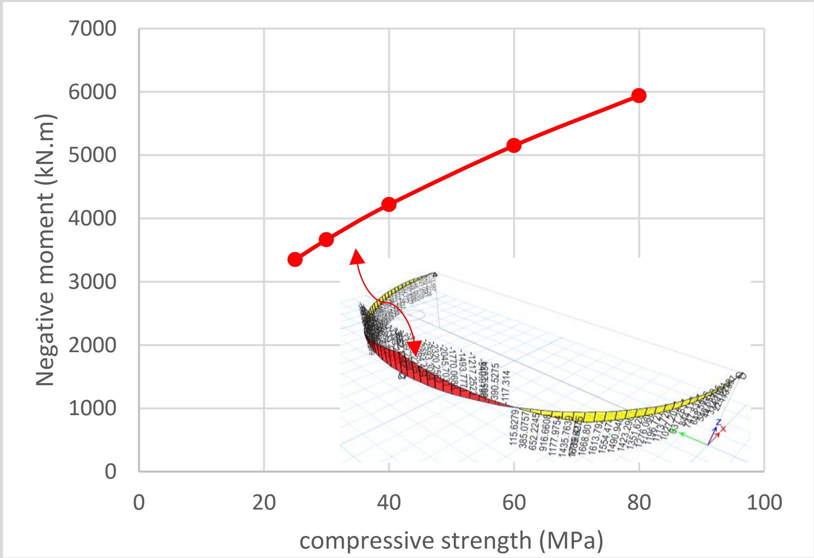

Figure 21. Effect of compressive strength variation on negative moment

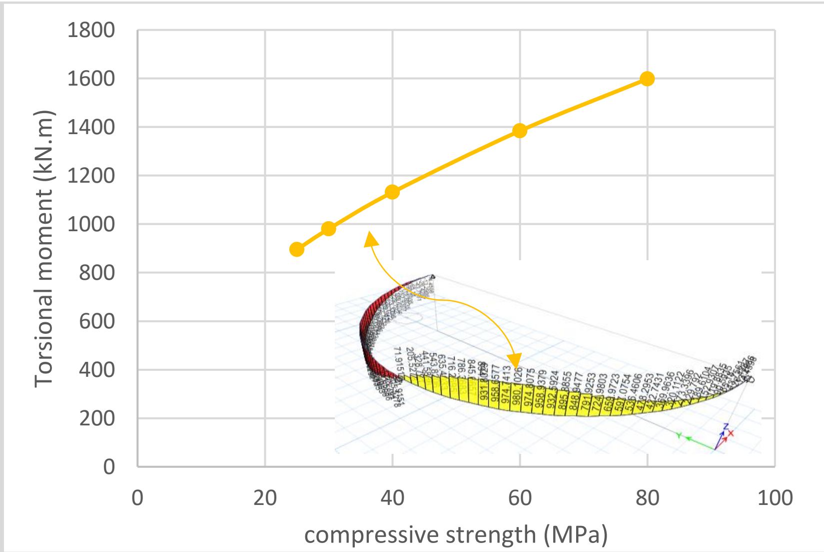

Figure 22. Effect of compressive strength variation on torsional moment

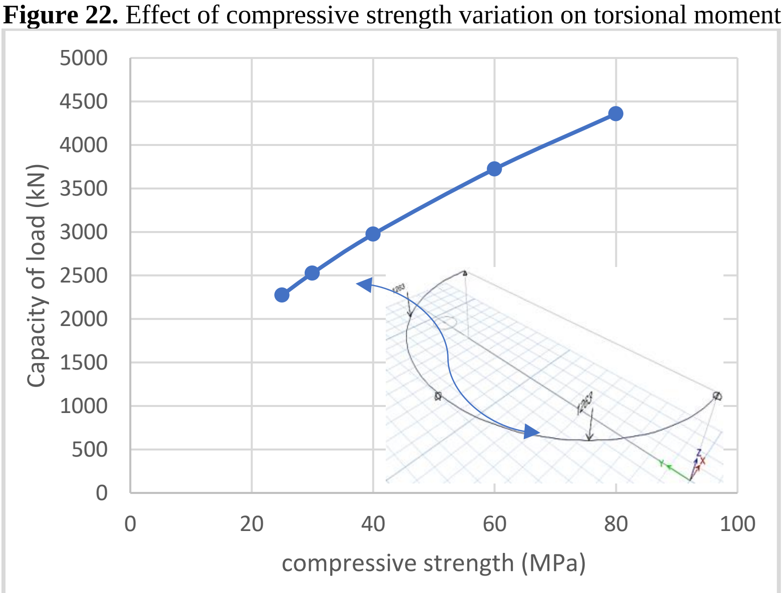

Figure 23. Effect of compressive strength variation on capacity of load

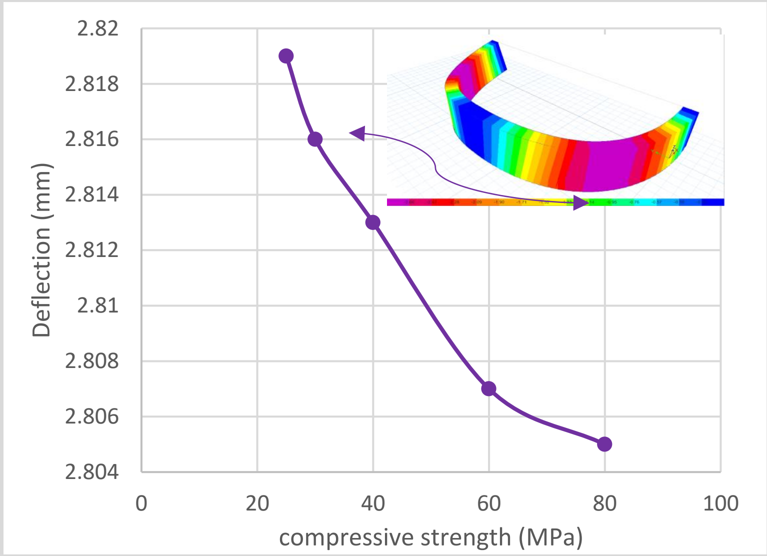

Figure 24. Effect of compressive strength variation on deflection

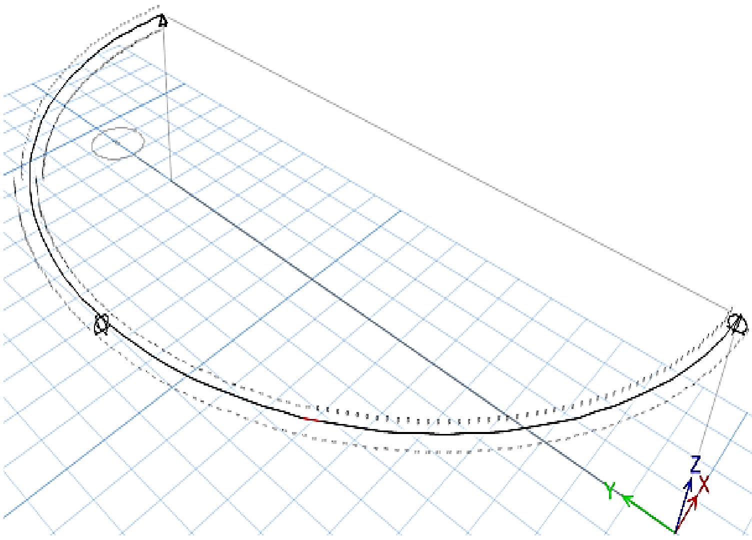

Figure 25. Location of failure of a beam with 30 MPa compressive strength

3.3 The effect of the number of supports

Five semi-circular deep beams were designed and analysed according to different numbers of supports; 3, 4, 5, 6, and 7. Increasing number of supports leads to span shortening, which leads to:

- The maximum positive moments increase by about 36-47% when increasing number of supports by about 33-66%, Figure 26.
- The maximum negative moments increase by about 16-31% when decreasing number of supports by about 14-29%, Figure 27.
- The moments of torsion decrease by about 6-55% when increasing the number of supports by about 33-133% as shown in Figure 30.
- The load capacity increase by about 156-969% when increasing number of supports by about 33-133%, Figure 28.
- Increasing the number of supports by about 33-133% led to decreased deflection by about 37-84%, Figure 29.

The failure location is lying between supporting and loading zones, which refers to occurrence of torsion and shear failure. As an example, Figure 31 shows how the failure of semi-circular deep beam with seven supports occurred between supporting and loading points at external spans.

It is worth to note that the effect of increasing the number of supports on the amount of positive bending moment was nonlinear and convex. The reason for this is that the span length becomes less when the number of supports increases until the positive bending moment reaches its highest value at five supports, and then gradually decreases due to the effect of the span that adjacent to the outer span, so that the highest positive bending moment takes place in the external span. As for the negative bending moment, it was undulating due to the negative bending moment being affected by the number of supports.

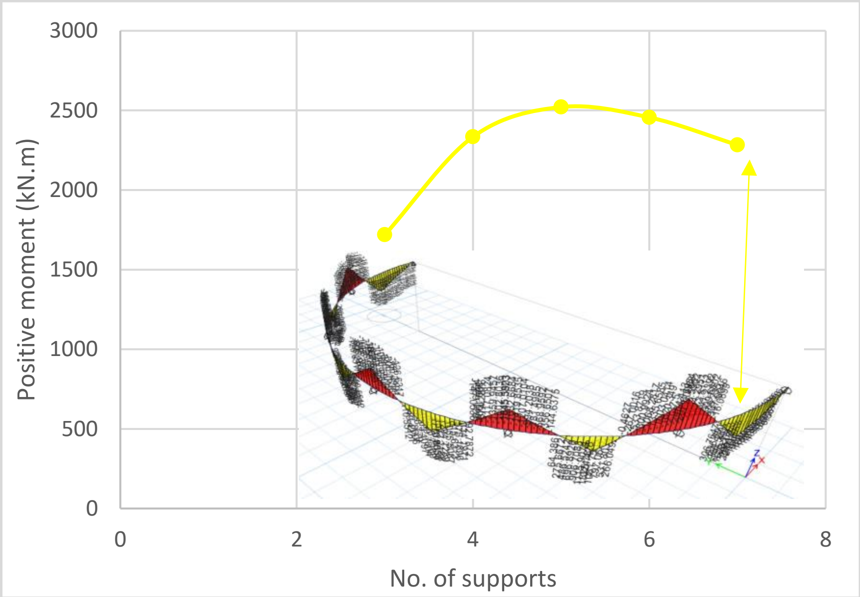

Figure 26. Effect of Number of supports variation on positive moment

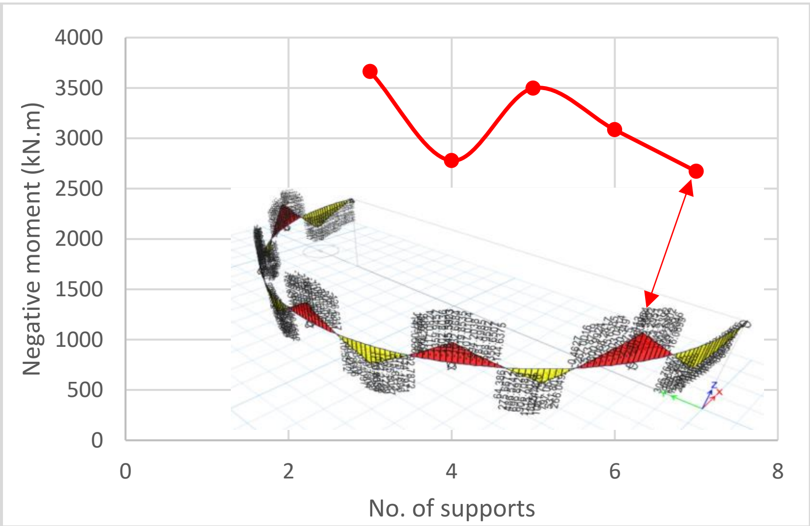

Figure 27. Effect of number of supports variation on negative moment

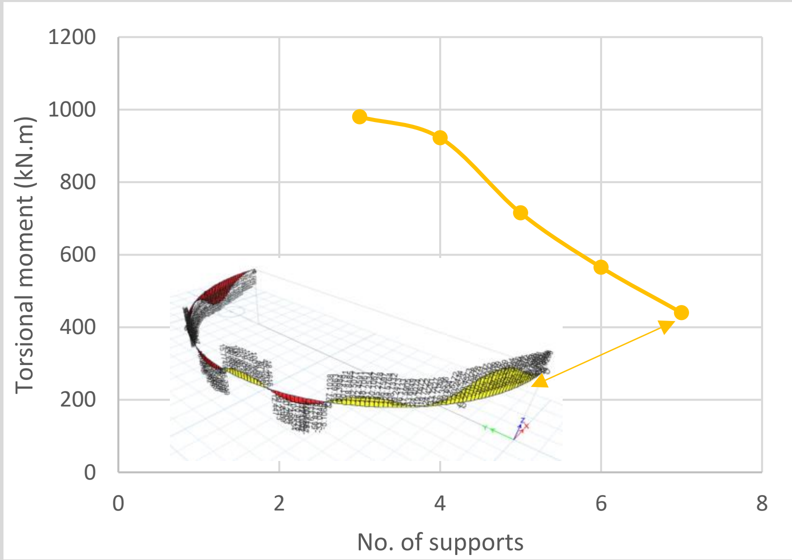

Figure 28. Effect of number of supports variation on torsional moment

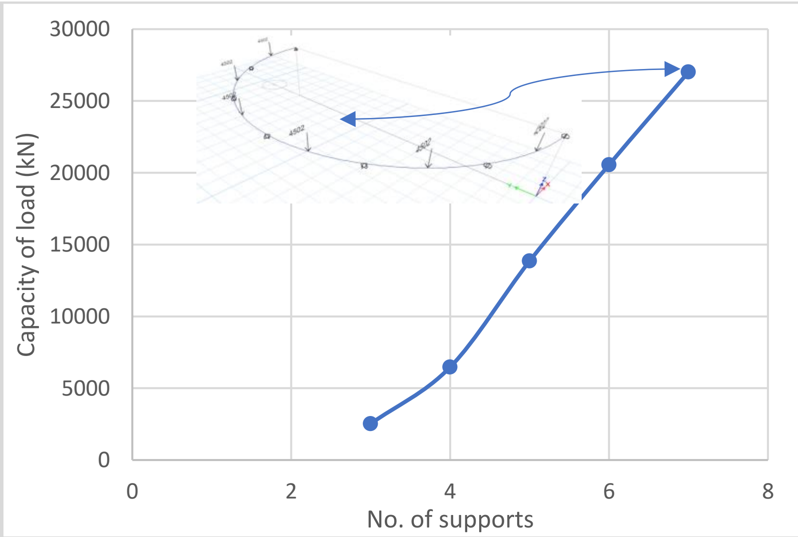

Figure 29. Effect of number of supports variation on capacity of load

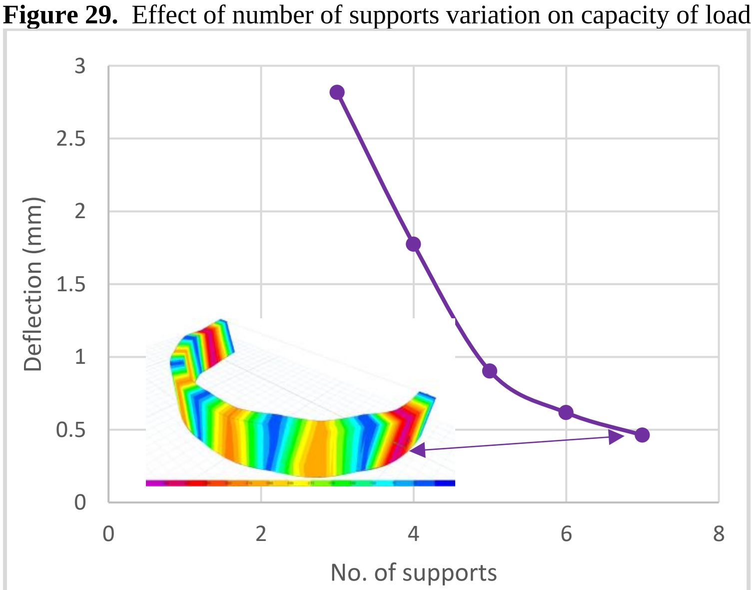

Figure 30. Effect of number of supports variation on deflection

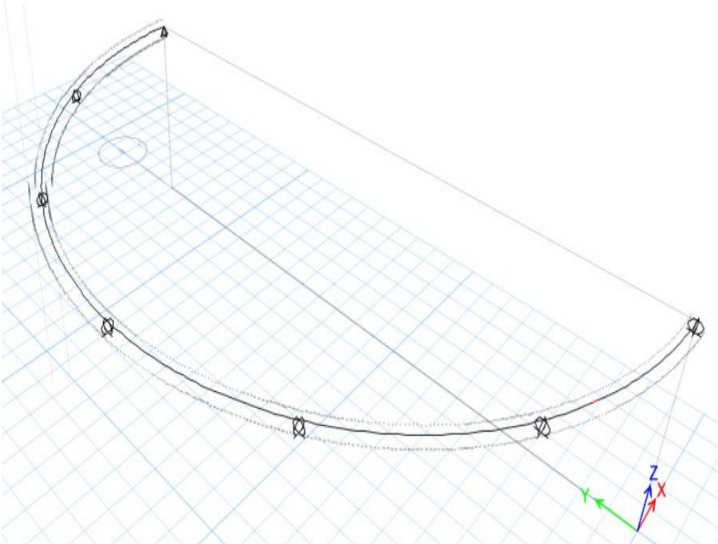

Figure 31. Location of failure of a beam with seven supports

4. Conclusions

Most of the parameters influencing the behavior and strength of the semicircular reinforced concrete deep beams were investigated in the current study. The use of the ETABS 2016 software, which relies on the finite element method, was easy and practical. Accordingly, the following conclusions were reached:

- The maximum positive bending moment, maximum negative bending moment, maximum torsional moments and midspan deflection decrease by about 0.3-20%, 2.4-25%, 2-24% and 29-85%, respectively, when beam radius decreases by 16-66%. Whereas this radius decrease leads to increase the load capacity by about 23-158%. That can be attributed to span length shortening that caused be radius decrease.
- The maximum positive bending moment, maximum negative bending moment, torsional moment and load capacity increase by about 20-82%, 20-81%, 20-81% and 21-84% respectively, when the beam height decreases by 16-66%. While this height decrease leads to midspan deflection decrease by about 7-17%. The beam sectional area increases when increasing beam height, i.e., causes strength increase.
- The maximum positive bending moment, maximum negative bending moment, torsional moment and load capacity increase by about 200-1113%, 167-958%, 172-989% and 230-1368%, respectively when beam width increases by 50-200%. While this width increase leads to midspan deflection decrease by about 3-5%. The beam sectional area increases when increasing width, i.e., more strength.
- The maximum positive bending moment, maximum negative bending moment, torsional moment and load capacity increase by about 10-84%, 9-77%, 9-79% and 11-92%, respectively, when concrete compressive strength increase by 20-220%. While this concrete compressive strength increase leads to deflection decrease by about 0.1-0.5%. Increasing concrete compressive strength increases shear stress resistance.
- The maximum positive bending moment increases by about 36-47% when increasing number of supports by 33-66%. Maximum negative bending moment increases by about 16-31% when decreasing number of supports by 14-29%. Torsional moment and midspan deflection decrease by about 6-55% and 37-84%, respectively when

number of supports increases by 33-133%. Whereas the load capacity increases by about 156-969%, when number of supports increases by 33-133%. The length of span decreases when increasing number of supports, resulting in higher strength capacity.

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