The effect of unequal load values on reinforced concrete deep beams

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Abstract. One of the most important problems facing the behavior and strength of deep beams is the asymmetry of the load in terms of magnitude despite its presence in the center of the beam span. It is known that the compression paths (struts) that transfer the load from the support points to the load points are usually symmetrical in deep beams when the 2-point load is central and equal, but in the current research work these struts are asymmetrical as a result of the inequality of load. This led to the strut with the higher load failing before that with the lower load. Therefore, the deep beam fails early. Twelve deep beam specimens were analyzed using SAP2000 software, which is based on the finite element method. Unequal 2-point loads of 33%-67%, 25%-75%, and 12.5%-87.5% were adopted. This case was studied using different values of concrete's compressive strength of 20, 30, and 40 MPa. Accordingly, the load capacity, midspan deflection, positive moments, and shear stresses decreased by about **24**-**13**%, **22**-**8**%, **11**-**10**%, and **15**-**13.5**%, respectively.

1 Introduction

Deep beams are members that satisfy (1) or (2) when they are loaded on one face and supported on the other in a manner that permits strut-like compression components to develop between the loads and supports: (1) The clear span (ln) is not higher than four times the total member depth (h). (2) Concentrated loads exist up to twice as far away from the face of the support [1]. Several authors have calculated the ultimate load capacity of conventionally reinforced concrete deep beams using empirical and semi-empirical formulae [2–5]. A few authors examined the parameters affecting deep beams [6–11]. Empirical formulas have been utilized the basis for deep beam design under the ACI-318 Code procedure since 2002. "A truss model of a structural member of a D-region in such a member, made up of struts and ties connected at nodes, capable of transferring the factored loads to the supports or to adjacent B-regions" is what Strut and Tie Modeling (STM) is defined as in ACI 318M-19 [1]. Throughout the deep member design process, STM provisions have been considered [12–16]. The plasticity lower bound hypothesis requires that simple yield requirements be satisfied in addition to equilibrium, and STM meets this need. According to the plasticity lower bound theory, a load will not cause the body to fail if its value allows the identification of a stress distribution that corresponds to stresses that maintain both internal and external equilibrium within the yield surface. If not, the true failure load of the body in issue will be equal to or less than the anticipated capacity of a structure under a lower bound theory. The strut and tie model is a very useful tool for researching and creating reinforced concrete members with D-regions [17-20]. The strength and behavior of reinforced concrete deep beams have been examined by certain authors in relation to the effects of beam width (b), depth, and concrete compressive strength (*f'c*). The authors arrived at the conclusion that a deeper beam's load capacity rises as its width does because it expands the struts' diameters. As the depth increases, the shear span (a) decreases and the load capacity rises as a result. The load capacity of deep beams to loads is increased by increasing the concrete's strength to compression, which also strengthens the struts [21-24].

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That is right that the STM is very important for analyzing deep beams because it reflects the reality of the stress transfer from load points to support points. The finite element method is also considered one of the important methods used by the authors to analyze deep beams. The reason for this is that the finite element method can represent any dimensions of a deep members and shows the stresses and strains inside these deep members with extreme accuracy, while the authors can apply any type of load to these deep members [6, 15, 16, 20, 21].

The asymmetry of the load in terms of magnitude despite its presence in the center of the beam span is one of the most significant issues affecting the behavior and strength of deep beams. It is well known that in deep beams, when the load is central and equal, the compression struts that transmit the load from the loading to the supporting points are often symmetrical. However, in the current study work, these struts are asymmetrical due to the inequality of load.

2 Finite Element Modeling

While the deep beam design was based on ACI 318-19, the finite element modeling was conducted using SAP2000 software.

2.1 SAP2000 Software Finite Element Modeling

The current work entails analyzing the impact of unequal 2-point loading values on the behavior and strength of twelve reinforced concrete deep beam specimens using the SAP2000 computer software. For the simply supported reinforced concrete deep beam design, the ACI 318-19 code was applied. A single deep beam is known to be split up into several finite elements. There were 118 of these finite elements in a single beam. Based on an analysis of the optimal number that ensures the necessary precision while reducing time and effort, this number was selected. For the sake of the present analysis, reinforcing steel bars were supposed to behave as an elastic, completely plastic material in both compression and tension.

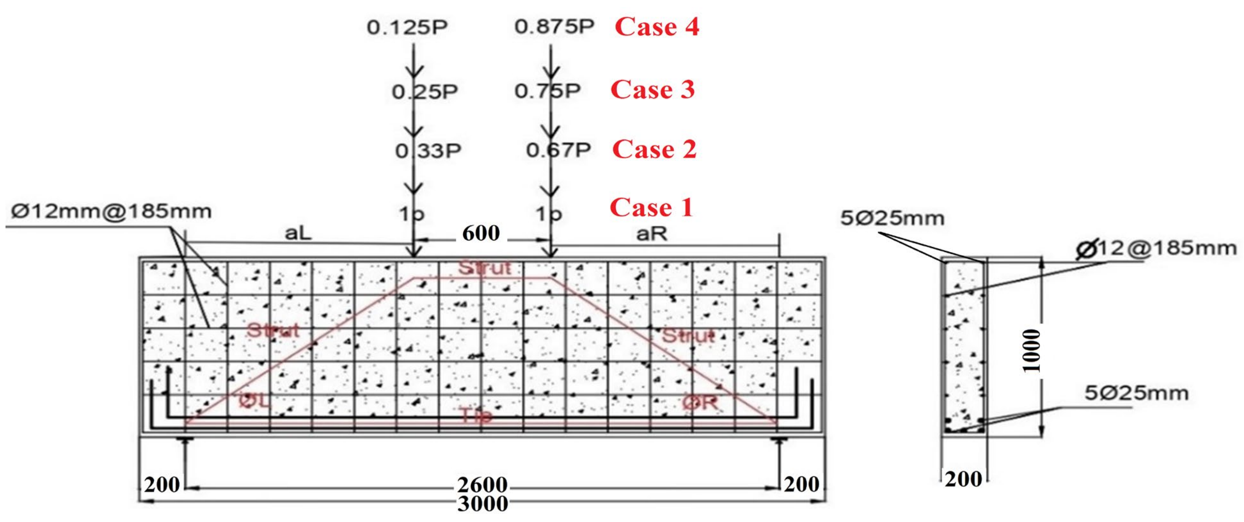
2.2 Inequality loading study cases

Table 1, Figures 1 and 2 present in detail the twelve simply supported deep beams made of reinforced concrete. The beam's length is 3000 mm, and its clear span measures 2600 mm, with a width of 200 mm and a height of 1000 mm. Within the minimum reinforcement ratios stipulated by the ACI 318-19 Code, all beams were reinforced in the same way. The shear reinforcement was ϕ12 mm @ 185 mm center/center, while the main reinforcement was made up of 5ϕ25 mm steel bars.

Three equal groups; A, B, and C, comprise these twelve deep beams. The first group (A) had a concrete compressive strength of 20 MPa, the second group (B) had a concrete compressive strength of 30 MPa, and the third group (C) had a concrete compressive strength of 40 MPa. The first specimen is exposed to two equal loads. The second specimen is exposed to a third of the load on the left side and two-thirds of the load on the right side. The third specimen is exposed to a quarter of the load on the left side and three-quarters of the load on the right side. The fourth specimen exposed to one-eighth of a load on the left side and seven-eighths of a load on the right side. This distribution was repeated three times in three groups in which the concrete's compressive strength was changed by 20, 30, and 40 MPa.

Table 1. Unequally loaded specimens

No.	Group	*f'c* (MPa)	Load Type	Sketch
1	A	20	1P-1P	1P 1P
2			0.33P-0.67P	0.33P 0.67P
3			0.25P-0.75P	0.25P 0.75P
4			0.125P-0.875P	0.125P 0.875P
5	B	30	1P-1P	1P 1P
6			0.33P-0.67P	0.33P 0.67P
7			0.25P-0.75P	0.25P 0.75P
8			0.125P-0.875P	0.125P 0.875P
9	C	40	1P-1P	1P 1P
10			0.33P-0.67P	0.33P 0.67P
11			0.25P-0.75P	0.25P 0.75P
12			0.125P-0.875P	0.125P 0.875P



Front view Side view

Fig.1. Deep beam unequal loading, dimensions, reinforcement and supports, all dimensions are in mm

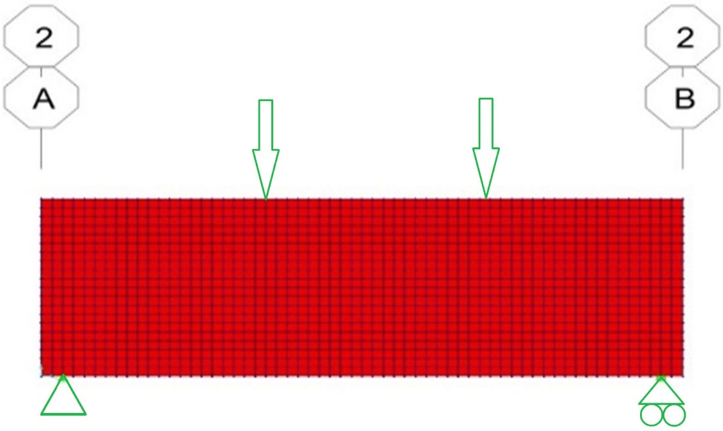
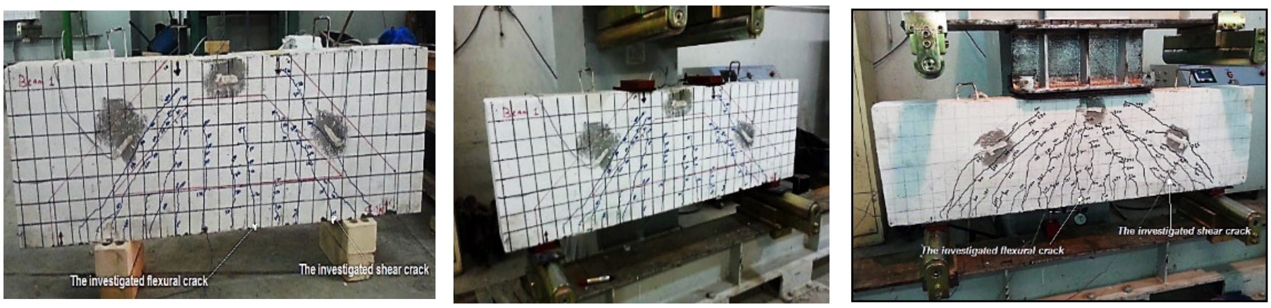


Fig. 2. Deep beam SAP2000 finite element modeling

2.3 Modeling Verification

Re-analyzing the three simply supported beams below (taken from previous work by the same authors of the current research [20]) allowed the authors to confirm their finite element modeling (Figure 3). The results demonstrated the accuracy of the modeling, particularly given Table 2's highest experience difference was less than 9%.



One concentrated load Two concentrated loads Uniformly distributed load

Fig. 3. Verification of finite elements by experimental investigation from previous work by the same authors of the current research, [20]

Table 2. Finite element verification

No.	Load Type	Experimental [20]		Numerical		Difference	
		Load Capacity (kN)	Midspan Deflection (mm)	Load Capacity (kN)	Midspan Deflection (mm)		
1	Single load	355	5.73	384	6.1	8%	6%
2	2 point load	562	8.62	586	9.26	4.3%	7.4%
3	Uniform load	547.8	7.57	582	8.23	6%	8.7%

2.4 Material Properties

Deep beams are modeled using concrete and steel reinforcement. In the current modeling, each type of element is utilized to represent the materials of a certain beam. The material properties are displayed in Table 3 together with the Poissons ratio (*v*), concrete strength in compressive (*f'c*), modulus of elasticity of steel bars (*Es*), modulus of elasticity of concrete (*Ec*), and yield stress of steel bars (*fy & fys*).

Table 3. Properties of the materials utilized

Concrete				Reinforcing Steel	
Ec (MPa)	Es (MPa)	f'c (MPa)	Poisson`s ratio(v)	fy (MPa)	fys (MPa)
24000	200000	20	0.21	440 for ϕ12mm	420
30100		30			
32800		40		410 for ϕ25mm	

3 The Influence of Loading Inequality

The results of load capacity, maximum positive moments, maximum shear stresses, maximum deflection, and failure location of all beams were determined using SAP2000 software. These results are reported in the following paragraphs**.** Table 4 shows the analysis of deep beams for the current parametric investigation. It was found that the load capacity, midspan deflection, positive moments and shear stresses decrease as the loading inequality increases.

Table 4. Results of load inequality

No.	Group	*f'c* (MPa)	Load Type	Load capacity (kN)	Decrease in load capacity	Max. positive moment (kN.m)	Decrease in moment	Max. shear (kN)	Decrease in Max. shear	Deflection (mm)	Decrease in Deflection
1	A	20	1P-1P	900	0	453	0	456	0	1.02	0
2			0.33P-0.67P	750	20%	407	10.2	410	10%	0.852	16.5%
3			0.25P-0.75P	700	22%	394	13%	396.6	13%	0.807	21.5%
4			0.125P-0.875P	680	24%	402.5	11%	390	15%	0.801	22%
5	B	30	1P-1P	1000	0	503.9	0	506.2	0	0.923	0
6			0.33P-0.67P	900	10%	488.8	3%	490	3.2%	0.814	12%
7			0.25P-0.75P	880	12%	494.5	2%	497	1.8%	0.807	12.5%
8			0.125P-0.875P	800	20%	472	7%	475.8	6%	0.844	9%
9	C	40	1P-1P	1100	0	554	0%	556	0	0.931	0
10			0.33P-0.67P	1050	5%	540	3%	480	14%	0.887	4.7%
11			0.25P-0.75P	1000	9%	520	6%	485	13%	0.841	10%
12			0.125P-0.875P	960	13%	501	10%	470	13.5%	0.852	8%

3.1 The Effect of Load inequality when f'c=20 MPa, Group A

In case *f'c*=20 MPa, when the 2-point load is unequal, the applied load's capacity varies considerably. The following were the outcomes due to unequal 2-point loads of 33%-67%, 25%-75%, and 12.5%-87.5%. As seen in Figure 4, load capacity drops by 20%, 22%, and 24%, respectively. Figure 5 shoes the maximum midspan deflection drops by 16.5%, 21.5%, and 11%, respectively. Figure 6 shows the maximum positive moment drops by 10.2%, 13%, and 11%, respectively. Finally, Figure 7 illustrates the maximum shear stresses drop by 10%, 13%, and 15%, respectively.

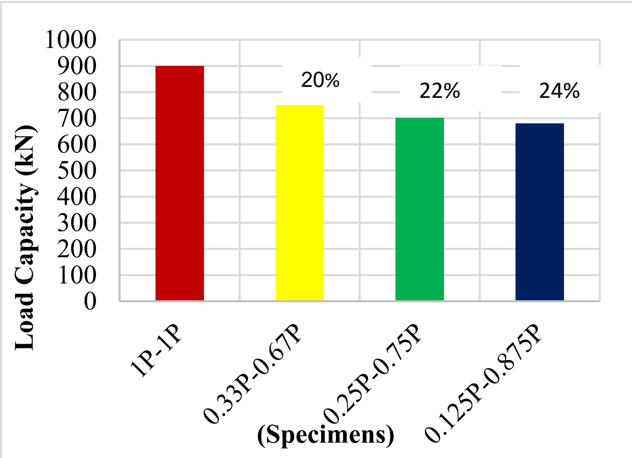


Fig. 4. Load capacity vs. unequal load for group A

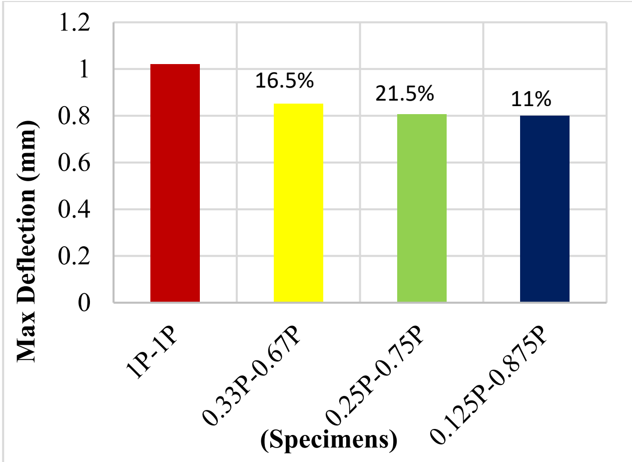


Fig. 5. Maximum Midspan Deflection vs. unequal Load for group A

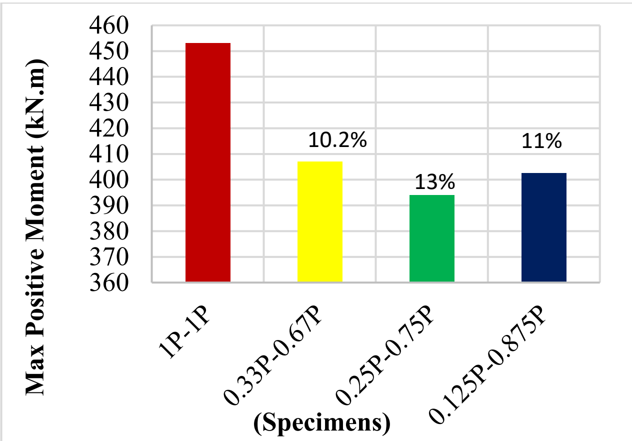


Fig. 6. Max. Positive Moment vs. unequal load for group A

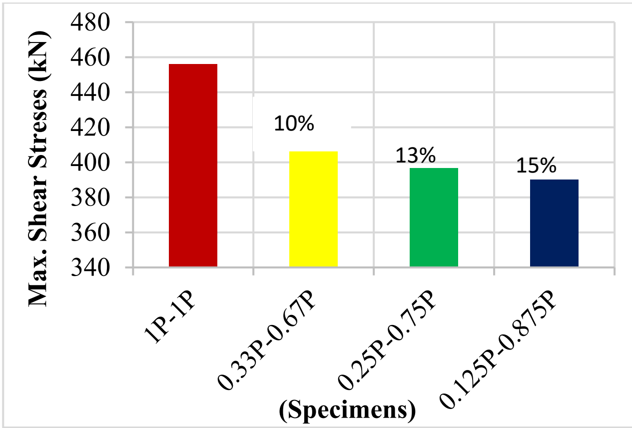


Fig. 7. Max. shear stresses vs. unequal load for group A

3.2 The Effect of Load inequality when f'c=30 MPa, Group B

When the load is unequal, as in the case of *f'c*=30 MPa, the applied load's capacity fluctuates significantly. The results of the unequal 2-point loads of 12.5%-87.5%, 25%-75%, and 33%-67% were summarized. Figure 8 illustrates load capacity drops by 10%, 12%, and 20%, respectively. Figure 9 shows the maximum midspan deflection drops by 12%, 12.5%, and 9%, respectively. Figure 10 clarifies the maximum positive moment drops by 3%, 2%, and 7%, respectively, while Figure 11 presents the maximum shear stresses fall by 24%, 42.8%, and 58%, respectively.

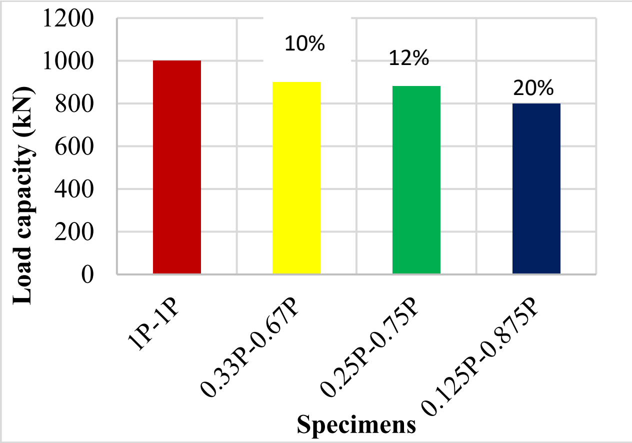


Fig. 8. Load capacity vs. unequal load, group B

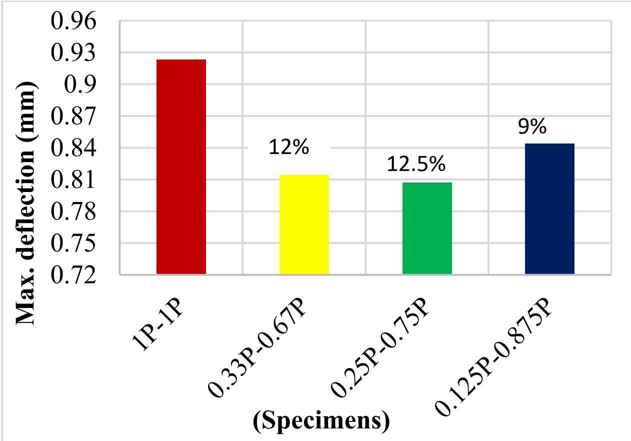
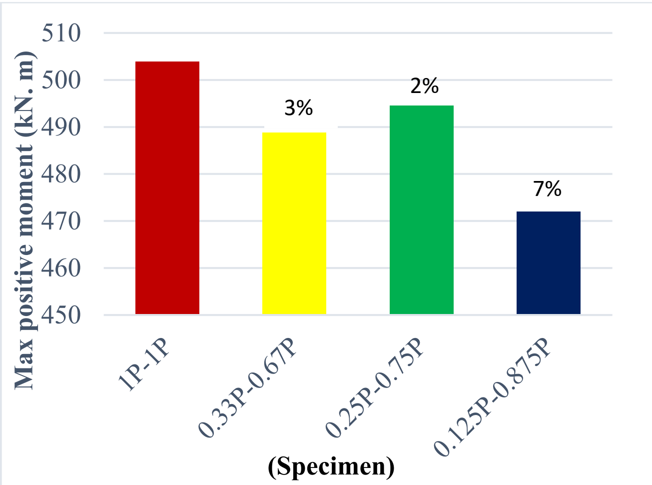


Fig. 9. Max. Midspan deflection vs. unequal load, group B



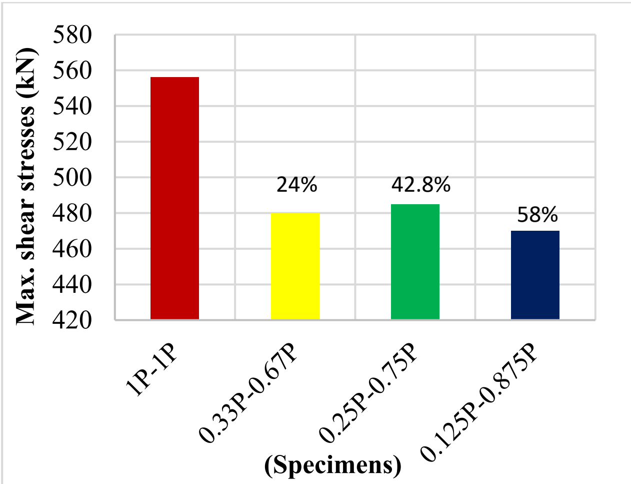


Fig. 10. Max. Positive shear stress vs. unequal load, group B

Fig. 11. Max. Positive shear vs. unequal load, group B

3.3 The Effect of Load inequality when f'c=40 MPa, Group C

The applied load's capacity fluctuates significantly when the load is unequal, as in the case of *f'c*=40 MPa. The following were the outcomes due to unequal 2-point loads of 33%-67%, 25%-75%, and 12.5%-87.5%. Figure 12 illustrates the 5%, 9%, and 13% reduction in load capacity, respectively. Figure 13 shows the maximum midspan deflection drops by 4.7%, 10%, and 8%, respectively. The maximum positive moment diminishes by 3%, 6%, and 10% are summarized in Figure 14. Figure 15 shows the maximum shear stress decreased by 14%, 13%, and 13.5%.

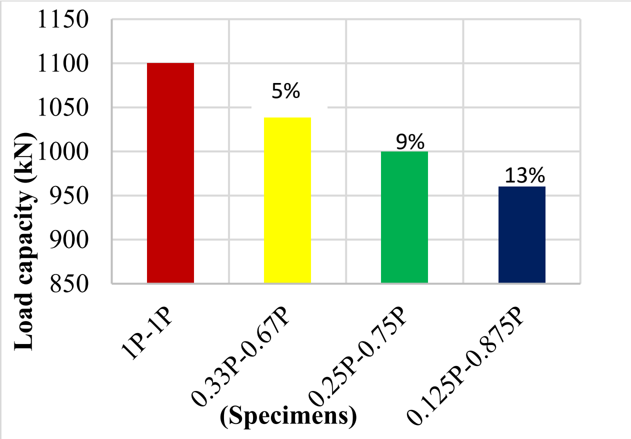


Fig. 12. Load capacity vs. unequal load for group C

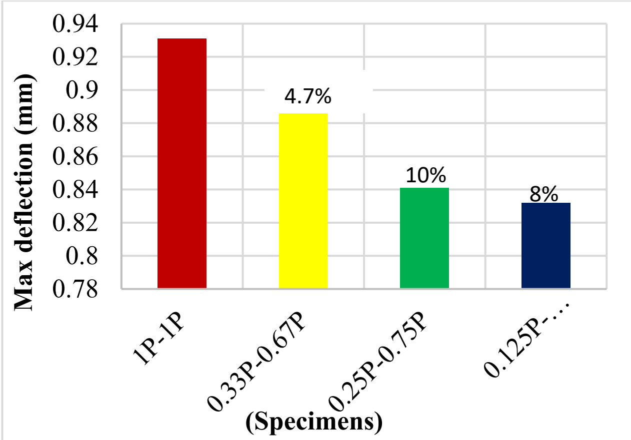


Fig. 13. Max. Deflection vs. unequal load for group C

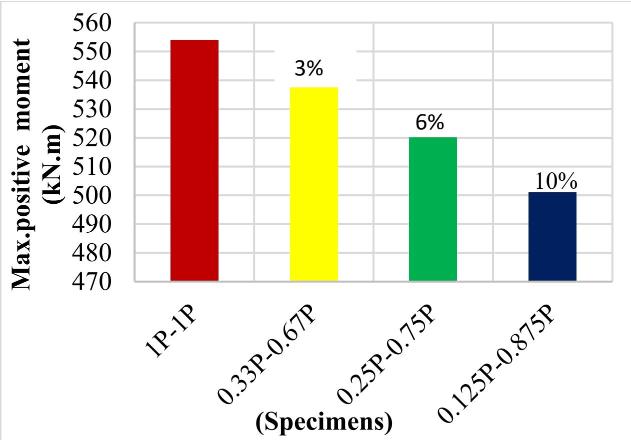


Fig. 14. Max. Positive Moment vs. unequal load for group C

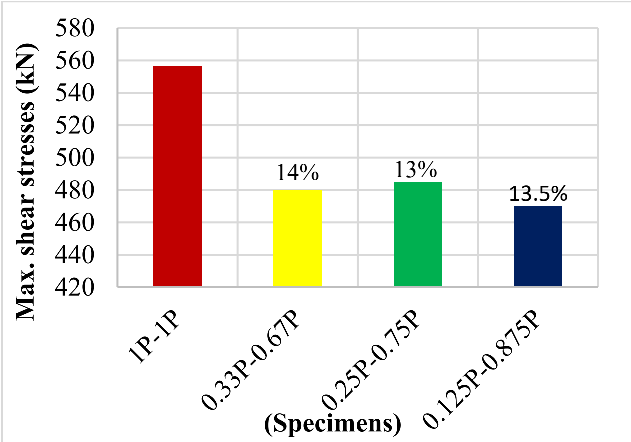


Fig.15. Max. shear vs. unequal load for group C

4 Discussion Of Results

The loading inequality in terms of value is one of the issues that deep beams and other constructions face. In other words, although the load is inequality in terms of value, it is positioned in the middle of the deep beam. As a result, the subject of the current study was divided into four groups: equal, one-third–two-thirds, one-quarter–three-quarters, and one-eighth–seven-eighths. The aforementioned plan was conducted twice more, using varying concrete strengths (20, 30, and 40) MPa, as the compressive strength of concrete is the most crucial parameter influencing the strength and behavior of reinforced concrete deep beams. It was found that when the inequality between the two applied loads grows, the deep beam load capacity, midspan deflection, positive moments, and shear stresses all decrease. Whereas increasing the load inequality from equal (50%-50%) to unequal by (12.5%-87.5%) resulted to a decrease in load capacity, midspan deflection, positive moments, and shear stresses by roughly 24-13%, 22-8%, 11-10%, and 15-13.5%, respectively. This is because, as the applied load becomes unequal, the stresses are focused in the strut on the strut transferring the heavier load, which fails sooner and causes the deep beam as a whole to fail earlier.

As the concrete's resistance to compression rises, the aforementioned decrements are less affected. It makes sense since the strut near the heavier load—which fails sooner—becomes stronger as the concrete's resistance to compression increases. Therefore, the values of load capacity, midspan deflection, positive moments, and shear stresses as a result of increasing the load inequality fall by 13%, 8%, 13%, and 13.5%, respectively, when concrete's compressive strength increases from 20 to 40 MPa.

5 Conclusion

It was found that the deep beam load capacity, midspan deflection, positive moments, and shear stresses all decrease with an increase in the inequality between the two applied loads. This is because the stresses in the strut on the strut carrying the larger load concentrate when the applied load becomes unequal, leading to the failure of the strut sooner and ultimately the failure of the deep beam as a whole. The previously indicated decrements are less impacted as the concrete's resistance to compression increases. It makes sense because as the concrete's resistance to compression improves, the strut near the larger load—which fails sooner—becomes stronger. On the basis of it, the findings that follow can be summed up as follows:

1- The load inequality from (50%-50%) to (12.5%-87.5%) reduces the load capacity, midspan deflection, positive moments, and shear stresses by about 24–20%, 16.5-22%, 10.2-11%, and 10-15%, respectively, if the concrete's compressive strength is 20 MPa.
2- The load inequality from (50%-50%) to (12.5%-87.5%) results in a decrease in the load capacity, midspan deflection, positive moments, and shear stresses of approximately10-20%, 12-9%, 3-7%, and 3.2-6%, respectively, if the concrete's compressive strength is 30 MPa.
3- When the concrete's compressive strength is 40 MPa, the load inequality from (50%-50%) to (12.5%-87.5%) causes a decrease in the load capacity, midspan deflection, positive moments, and shear stresses, which are approximately 5-13%, 3-10%, 14-13.5%, and 4.7-8%, respectively.
4- As a result of rising load inequality, the values of load capacity, midspan deflection, positive moments, and shear stresses drop by46%,64%,9%, and10%, respectively, as concrete's compressive strength rises from 20 to 40 MPa.

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