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Numerical investigation of the effect of support conditions on beam shear behaviour in full scale reinforced concrete beams

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Research Paper

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Numerical investigation of the effect of support conditions on beam shear behaviour in full scale reinforced concrete beams

In studies on beams in the literature, the beam elements are designed and tested as simply supported. Therefore, in this study, the behaviour of reinforced concrete (RC) beams under fixed support conditions was numerically investigated using ANSYS finite element software. The variables used in the study are the shear span/effective depth ratio (a/d) and stirrup spacing of the analysed specimens. In this study, 16 RC beams on a 1/1 scale were analysed in 4-point bending protocol. The a/d ratios were assumed to be 1.0, 2.0, and 3.0, in the test members produced. In addition, as another variable, the lateral reinforcement amount was designed and analysed at ϕ8/75, ϕ8/150 and ϕ8/300 mm spacings without stirrups. Load-displacement and stiffness graphs are drawn based on the numerical results. The numerical results were interpreted and compared based on the graphs drawn for each analysis, stress distribution, and damage occurrence in the experiments. The results indicated that the a/d ratio and number of stirrups had strong effects on the behaviour of the fixed supported beams. The results of the beam analyses obtained using ANSYS finite element software were consistent with the experimental results.

Key words:

fixed support, a/d ratio, reinforced concrete beam, experimental study, stirrup ratio, beam shear behaviour

Prethodno priopćenje

Alptuğ Ünal, Mehmet Kamanlı, Abdulkadir Solak, Salih Cengiz

Numeričko ispitivanje učinka uvjeta oslanjanja na posmično ponašanje grede u armiranobetonskim gredama realnih veličina

U istraživanjima o gredama u literaturi, gredni su elementi projektirani i ispitani kao jednostavno oslonjeni. Stoga je u ovom radu ponašanje armiranobetonskih (AB) greda u uvjetima upetog oslanjanja numerički ispitano pomoću računalnog programa ANSYS. Varijable primijenjene u istraživanju su omjer posmičnog raspona i statičke visine (a/d) te razmak spona analiziranih uzoraka. U ovom je radu analizirano 16 AB greda u mjerilu 1/1 tijekom ispitivanja savijanjem u četiri točke. Omjeri a/d uzeti su kao 1,0, 2,0 i 3,0 u odabranim elementima ispitivanja. Osim toga, kao druga varijabla, količina poprečne armature dimenzionirana je i analizirana kao ϕ8/75, ϕ8/150 i ϕ8/300 mm razmaka i bez spona. Na temelju numeričkih rezultata prikazani su grafovi odnosa opterećenja i pomaka te krutosti. Numerički rezultati interpretirani su i uspoređeni na temelju grafova prikazanih za svaku analizu, raspodjelu naprezanja i pojavu oštećenja u istraživanju. Rezultati su pokazali da su omjer a/d i broj spona snažno utjecali na ponašanje upeto oslonjenih greda. Rezultati analize greda dobiveni pomoću računalnog programa ANSYS bili su u skladu s eksperimentalnim rezultatima.

Ključne riječi:

upeto oslanjanje, omjer a/d, armiranobetonska greda, eksperimentalno ispitivanje, količina spona, posmično ponašanje grede

1. Introduction

Reinforced concrete (RC) structures are commonly used in construction systems worldwide, which makes RC beams one of the most important structural elements in buildings. RC beams are structural elements that transfer loads from building systems to columns. The behaviour of beams under internal and external forces is very important for structural safety. Therefore, it is necessary to determine the behaviour of RC beams under various loads. Because RC building systems have been widely used, various experimental and analytical studies have been conducted on an elemental basis [1-14]. These studies aimed to determine the behaviour of RC beams used in RC structures.

In several studies, beam elements were designed and analysed as simply supported [16-22]. However, because the beams in RC buildings are connected to columns, the beam bearings function neither as fully fixed bearings nor as fully simple bearings. However, beam bearings in RC buildings are considered closer to the fixed support condition [15, 23]. An RC beam test was performed on a frame system with beams embedded in columns, without producing a simply supported test member. The main purpose of this study is to address the research gap in the literature due to the limited number of studies that tested RC beams under fixed-support conditions.

In this study, the differences between the behaviours of RC beams under simple- and fixed-support conditions were investigated. Most previous experimental and analytical studies have been carried out at a 1:2 or 1:3 scale, and small-scale specimens were preferred because they were cost effective and because the test apparatus was not sufficiently rigid for full-scale specimens. However, the extent to which the behaviour of beams used in RC buildings is compatible with small-scale beams is not known. In addition, it is not known whether the actual beam behaviour is exhibited in the case of scaling. Therefore, it is necessary to determine the behaviour of 1:1 scale RC beams in future studies.

The stirrup spacing is very important in terms of the shear strength of RC beams. Many studies have been conducted on the effect of stirrup spacing on the behaviour of RC beams [1, 17, 19, 21]. In these studies, the effect of stirrups on the behaviour of RC beams was investigated, and important findings were obtained. However, the findings of these studies were related to RC beams tested under simple support conditions. Therefore, the effect of stirrups on the behaviour of RC beams tested under fixed support conditions should be investigated.

One of the most important properties of RC beams in terms of shear behaviour is the “shear span/effective depth (a/d)” ratio. Experimental studies have shown that an a/d ratio greater than 2.5 indicates a bending tendency of the beam, while an a/d ratio less than 2.5 indicates a shear tendency of the beam [20]. Many studies have been conducted to investigate the effect of a/d ratio on beam shear behaviour [1, 2, 4, 5, 12, 17, 18, 23-28]. In these studies, the effect of a/d ratio on shear behaviour was investigated by considering the beam height or beam length as a variable. In this study, the same beam dimensions were used for all test members, and a change in the a/d ratio was achieved by changing the locations of the loading points.

In light of these considerations, a numerical study was conducted to determine the shear behaviour of RC beams under fixed support conditions. In this study, 16 full-scale RC beam specimens were tested under monotonic loading. The specimens designed within the scope of the numerical study were analysed using ANSYS Workbench 19.2 finite element software in 4-point bending setup. The stirrup ratio and shear span/effective depth (a/d) ratio for RC beams under fixed support conditions were used as the parameters in this study. Load-displacement curves, stiffness graphs, and energy consumption graphs of the beams were drawn, and the results were compared. The results show that the a/d ratio and stirrup spacing of RC beams under fixed support conditions cause significant changes in the shear behaviour of the beam.

2. Material and method

In this study, 16 full-scale beam specimens were designed and analysed using ANSYS Workbench 19.2 finite element software in a 4-point loading setup. The support and loading conditions in the analysis model used in the numerical study were obtained from the experimental setup used by the authors at Konya Technical University, Department of Civil Engineering, Earthquake Research Laboratory [29-31].

2.1. Test specimens

The specimens were designed with identical dimensions and properties. The differentiating factors between the specimens were the stirrup ratio and support conditions. No stirrup was found in the first, fifth and ninth specimens (SRCB-1, FRCB-1, FRCB-5, FRCB-9), while stirrup was found in the second, sixth and tenth specimens (SRCB-2, FRCB-2, FRCB-6 and FRCB-10) at 300 mm, in the third, seventh and eleventh specimens (SRCB-3, FRCB-3, FRCB-7 and FRCB-11) at 150 mm, and in the fourth, eighth and twelfth specimens (SRCB-4, FRCB-4, FRCB-8 and FRCB-12) at 75 mm intervals. The specimens were designed to be full-scale. The specimens were 5000 mm in length. The distance between the beam-support points was 3750 mm. The beam cross section was designed as 250x500 mm. 3ϕ16 longitudinal reinforcement was used on beams. No other reinforcements were used for SRCB-1, FRCB-1, FRCB-5, and FRCB-9. SRCB-2, SRCB-3, SRCB-4, FRCB-2, FRCB-3, FRCB-4, FRCB-6, FRCB-7, FRCB-8, FRCB-10, FRCB-11, FRCB-12, 3ϕ16 longitudinal reinforcement, and 2ϕ12 montage reinforcement were found. The sizes and reinforcement properties of the specimens are shown in Figure 1, and their general properties are listed in Table 1.

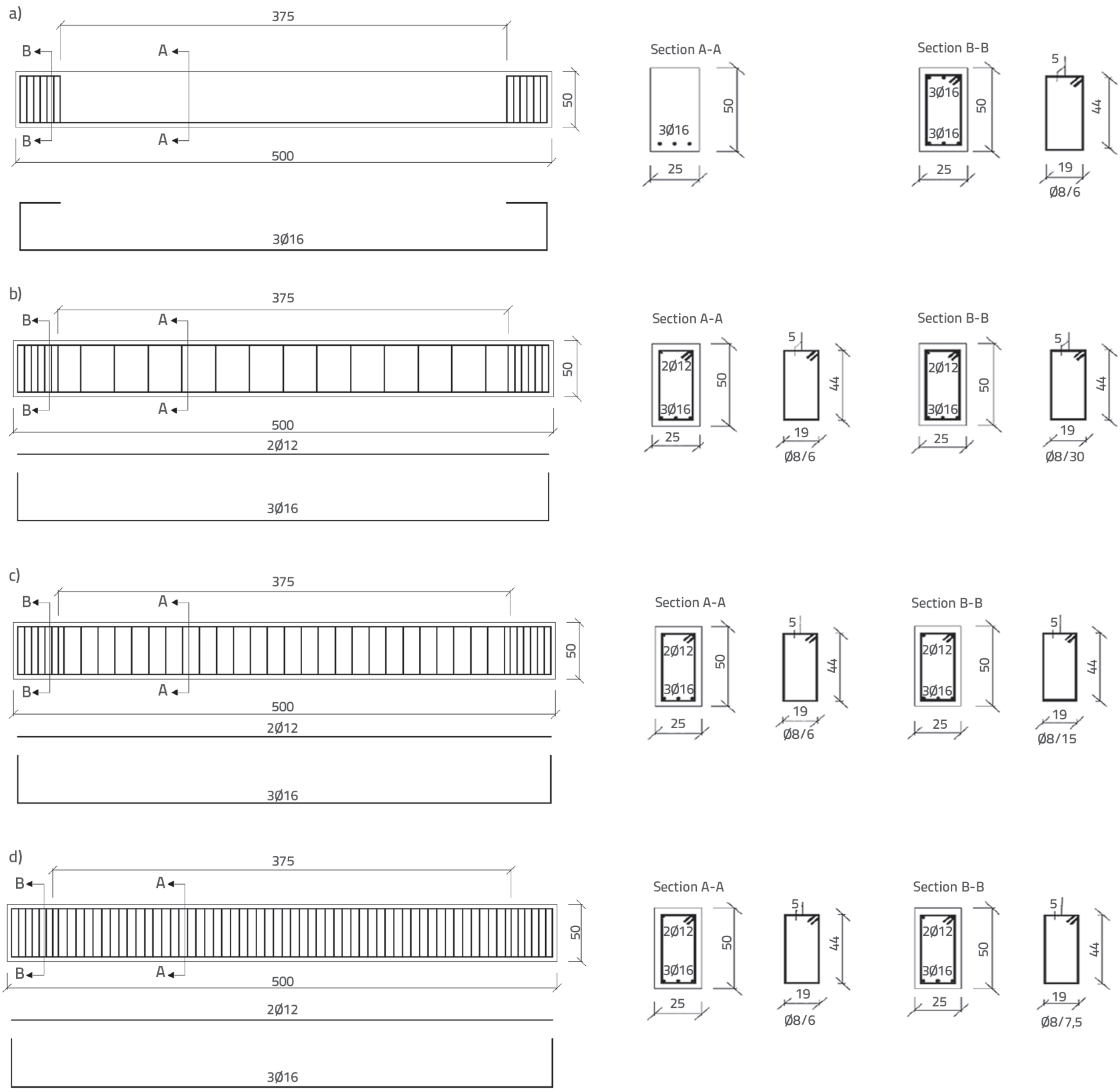

Figure 1. Properties of specimens: a) SRCB-1, FRCB-1, FRCB-5 and FRCB-9; b) SRCB-2, FRCB-2, FRCB-6 and FRCB-10; c) SRCB-3, FRCB-3, FRCB-7 and FRCB-11; d) SRCB-4, FRCB-4, FRCB-8 and FRCB-12 (Measure in cm)

The displacement capacities of the specimens were determined from the experimental data. A loading protocol was designed based on the displacement capacities of the specimens (Figure 7). A displacement-controlled loading method was applied to the specimens during analysis, and the load values corresponding to each displacement value were determined. Load-midpoint displacement graphs were plotted using the obtained data.

2.2. Materials

Because the specimens were designed at full scale, their material properties were considered appropriate. Therefore, concrete class C30 and reinforcement class S420 were selected to be the same as the specimens. The properties of the materials used in the specimens are listed in Tables 2 and 3.

A SOLID65 element was used to model the concrete. This element has eight nodes with three degrees of freedom at each node: node translation in the x, y, and z directions. This element can undergo plastic deformation in concrete applications, crack in three orthogonal directions, and crush under compression (Figure 2).

The following equation, proposed by Hognestad, was used to compute the multilinear isotropic stress–strain curve for the concrete [32]. The tensile strength of the concrete was

Table 1. General properties of specimens

Specimen name	a/d ratio	Support conditions	Longitudinal reinforcement	Montage reinforcement	Stirrup
FRCB-1	3	Fixed	3Ø16	–	–
FRCB-2	3	Fixed	3Ø16	2Ø12	Ø8/30
FRCB-3	3	Fixed	3Ø16	2Ø12	Ø8/15
FRCB-4	3	Fixed	3Ø16	2Ø12	Ø8/7.5
FRCB-5	2	Fixed	3Ø16	–	–
FRCB-6	2	Fixed	3Ø16	2Ø12	Ø8/30
FRCB-7	2	Fixed	3Ø16	2Ø12	Ø8/15
FRCB-8	2	Fixed	3Ø16	2Ø12	Ø8/7.5
FRCB-9	1	Fixed	3Ø16	–	–
FRCB-10	1	Fixed	3Ø16	2Ø12	Ø8/30
FRCB-11	1	Fixed	3Ø16	2Ø12	Ø8/15
FRCB-12	1	Fixed	3Ø16	2Ø12	Ø8/7.5
SRCB-1	3	Simply	3Ø16	–	–
SRCB-2	3	Simply	3Ø16	2Ø12	Ø8/30
SRCB-3	3	Simply	3Ø16	2Ø12	Ø8/15
SRCB-4	3	Simply	3Ø16	2Ø12	Ø8/7.5

Table 2. Multilinear isotropic stress–strain values of the concrete

Compressive strength	Strain (ε)					
	0.0005	**0.001**	**0.0015**	**0.002**	**0.0025**	**0.003**
29.44 MPa	11.10	19.04	23.80	25.39	23.8	19.04

determined by 4-point bending test to be appropriate for the loading condition applied in the experimental and numerical studies.

$$\sigma_c = f_c\left[\frac{2\varepsilon_c}{\varepsilon_{co}} - \left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)^2\right] \quad (1)$$

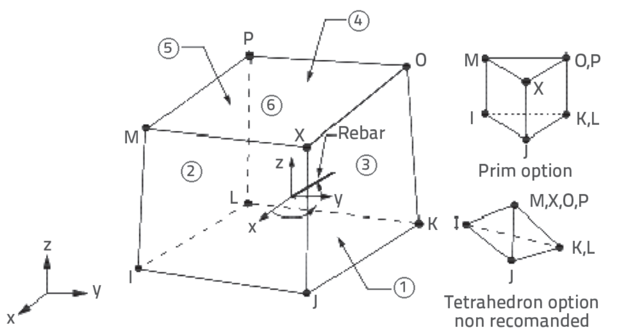

Figure 2. SOLID65 geometry (ANSYS User's Guide, 2018)

The stress-strain values determined according to the Hognestad model for concrete are listed in Table 2. The elastic modulus was calculated using the initial slope of the graph obtained from these values. The Poisson ratio is taken as 0.2 for both concrete samples. The modulus of elasticity for the concrete was 22216.25 MPa, and the ultimate tensile strength was 2.54 MPa.

Two-node linear displacement truss element LINK180 was adopted for the beam longitudinal and montage reinforcements and stirrups. The element is a uniaxial tension-compression element with three degrees of freedom at each node: node translation in the x, y, and z directions (Figure 3).

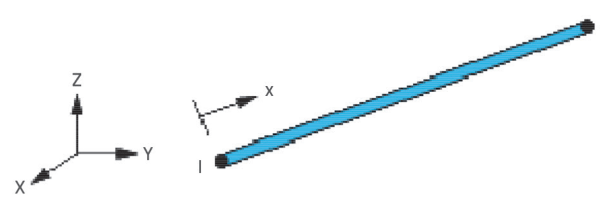

Figure 3. LINK180 geometry (ANSYS User's Guide, 2018)

The beams were designed according to Eurocode-2 and ACI 318 standards. Because the beam dimensions were modelled on the 1/1 scale used in the experimental study, the reinforcement was reduced by the same proportion. Therefore, 8 mm diameter longitudinal reinforcements and 6 mm diameter stirrups were used for the beams.

"The William–Warnke constitutive model for the triaxial behaviour of concrete" was used for the crack model of the

Table 3. Properties of steel

Average yield strength [MPa]		**Average tensile strength** [MPa]	**Place of use**
Ø8	378.72	454.88	Stirrup
Ø12	386.97	485.37	Montage
Ø16	409.25	509.72	Longitudinal

concrete material [33]. The shear transfer coefficients was taken as 0.3 for the open crack, and as 1.0 for the close crack. These coefficients were used to reduce the error rate when obtaining the load-displacement relationship derived using the finite element method. The mechanical behaviour of the reinforcement was assumed to be elastic bilinear under monotonic stress.

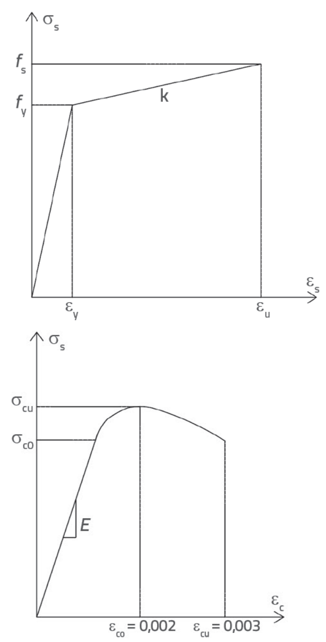

Figure 4. Constitutive models of: a) reinforcement; b) concrete under compression

Figure 5. Pre-experimental appearance of specimens

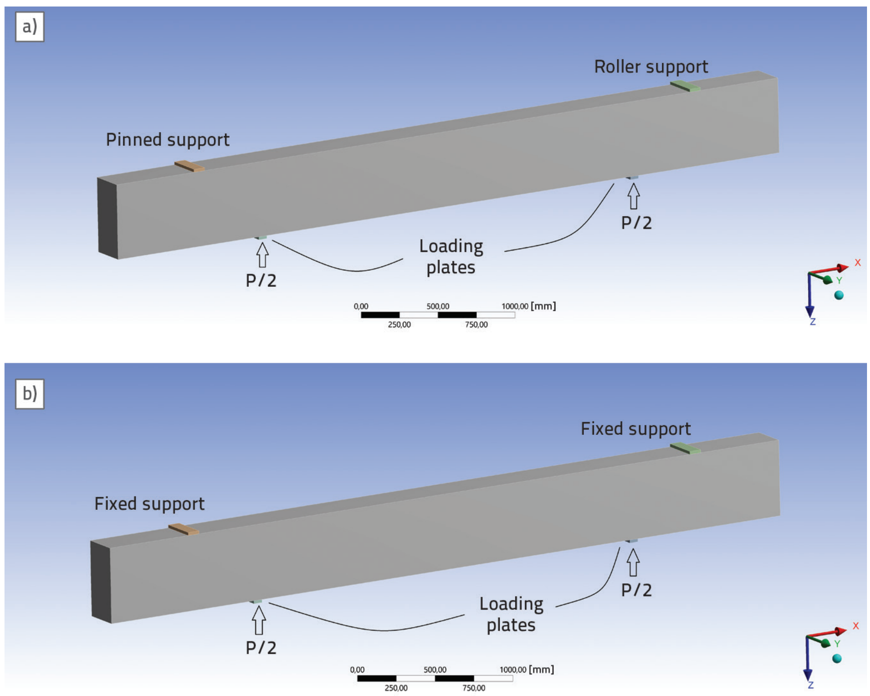

Figure 6. Analysis conditions: a) simply supported; (b) fixed

The reinforcement initially exhibited a linear elastic part, followed by a yield point, strain hardening, and fracture. The main inputs for the steel material model were the modulus of elasticity, tangent modulus, and yield strength. The tangent modulus (k) was set as 20 MPa in the analysis. The constitutive models for steel and concrete under compression are shown in Figure 4.

Sixteen specimens were analysed under monotonic loading using ANSYS Workbench 19.2. The support and loading conditions in the analysis model used in the numerical study were obtained from the experiment conducted by the authors at Konya Technical University, Department of Civil Engineering, Earthquake Research Laboratory (Figure 5). In this model, the bearings and loading plates were designed to be rigid (Figure 6). The displacement capacities of the specimens were determined from the experimental data. A loading protocol was designed based on the displacement capacities of the specimens (Figure 7). A displacement-controlled loading method was applied to the specimens during analysis, and the load values corresponding to each displacement value were determined. Load-midpoint displacement graphs were plotted using the obtained data.

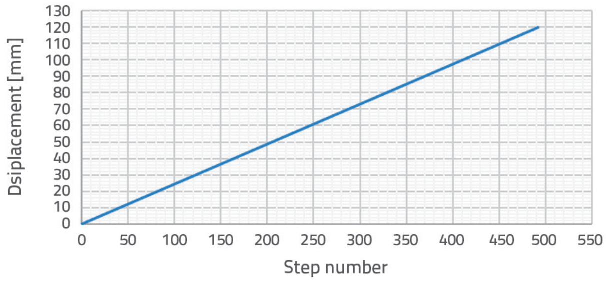

Figure 7. Loading protocol

The 16 test members designed in this study were tested under monotonic loading. The same loading program was applied to all the test members. The analyses were performed under displacement control. The loading continued until significant damage occurred in the test members. The cracks and damages that occurred in the test elements during the experiment were recorded. Load–midpoint displacement graphs were drawn according to the data obtained from the potentiometric rulers and load cell. In addition to graphical comparisons, the behavioural patterns of the test elements were compared. For this purpose, the fracture forms and crack distributions in the experiments were comparatively analysed. The data obtained during the analysis were processed, graphs were drawn, and the analytical results were interpreted.

3. Results

3.1. Effect of a/d ratio on the behaviour of fixed-support beams

The specimens were compared to examine the effect of a/d ratio on the behaviour of the test elements. For this purpose, specimens with the same features but different a/d ratios were comparatively analysed.

The specimens with low a/d ratios had higher load-carrying capacities than those with high a/d ratios. All specimens in the test members without stirrups were damaged owing to shear fracture. One of these specimens, FRCB-1 and FRCB-9, first reached the yield point and then collapsed owing to shear failure. However, FRCB-5 failed because of undergoing shear failure before reaching the yield point. All the specimens with stirrups reached the yield point. Among the welded specimens, all test members with an a/d ratio of 3 exhibited flexural behaviour. Except for the FRCB-5 specimen, all specimens with a/d ratios of 2 exhibited flexural behaviour.

The stirrup spacing had a significant influence on the behaviour of the test elements. Test members with stirrups exhibited more ductile behaviour than those without stirrups. As the stirrup spacing decreased, stresses were distributed in the element. The stress distribution obtained from the analytical study was compared to that obtained from the experimental study, Figure 8. With more stress distribution, the energy consumption also increased. The stresses in the specimens were concentrated between the loading points and bearing areas. Therefore, specimens with a low stirrup spacing are more susceptible to shear behaviour.

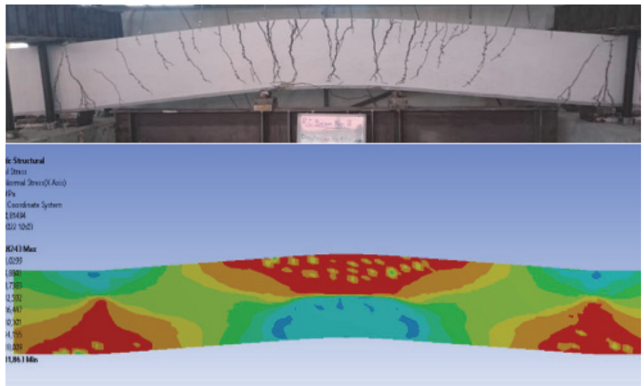

Figure 8. Experimental presentation and numerical simulations

Table 4. Comparison of load-carrying capacities of test elements

Test element	Compared to	Load carrying capacity
FRCB-9	FRCB-1	100.5 % more
FRCB-9	FRCB-5	106.3 % more
FRCB-10	FRCB-6	47.1 % more
FRCB-10	FRCB-2	118.7 % more
FRCB-6	FRCB-2	48.7 % more
FRCB-11	FRCB-7	50.1 % more
FRCB-11	FRCB-3	129.1 % more
FRCB-7	FRCB-3	53.2 % more
FRCB-12	FRCB-8	50.0 % more
FRCB-12	FRCB-4	120.3 % more
FRCB-8	FRCB-4	46.9 % more

Test elements with the same geometric properties and reinforcement arrangement but different loading points were compared (Table 4). The load-displacement curves of the test elements were plotted and compared.

The load-displacement graphs drawn from the experimental and analytical studies are shown in Figure 9, chapter 3.2. Compatible results were obtained when the graphs obtained from the numerical analysis were compared with the experimental results. The initial stiffness of the samples with a/d ratios of 1 was greater than that of the samples with a/d ratios of 2 and 3.

3.2. Effect of support conditions on the behaviour of RC beams

The stress distributions of the specimens were examined during the analysis. Load-midpoint displacement graphs were drawn according to the load values corresponding to each displacement. Figures 9 to 11 presents a comparison of specimens with the same properties but different support conditions.

The load-carrying capacities of the test elements under fixed support conditions were greater than those under simple

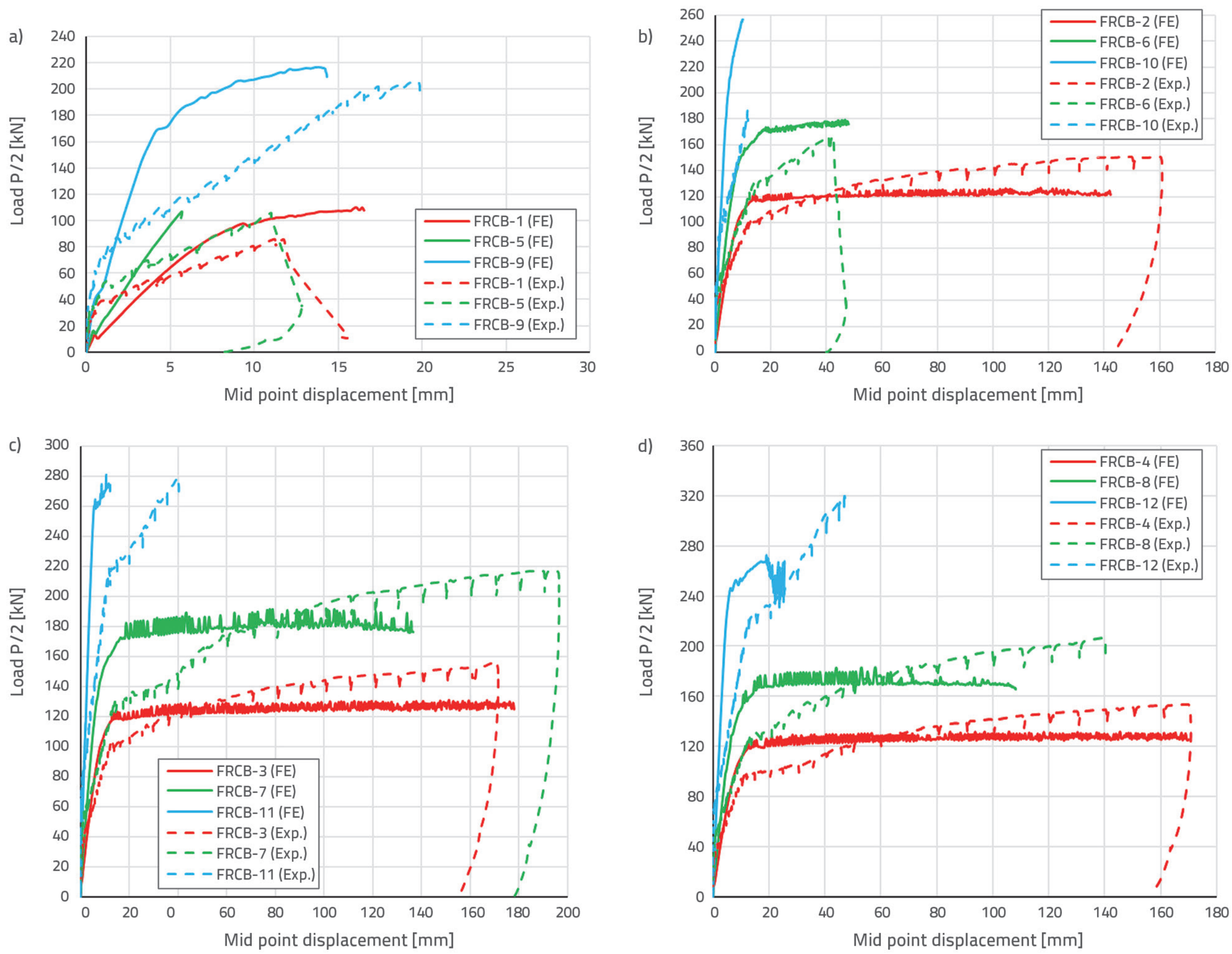

Figure 9. Load-mid point displacement curves: a) Non stirrup; b) Ø8/30 stirrup; c) Ø8/15 stirrup; d) Ø8/7.5 stirrup [30]

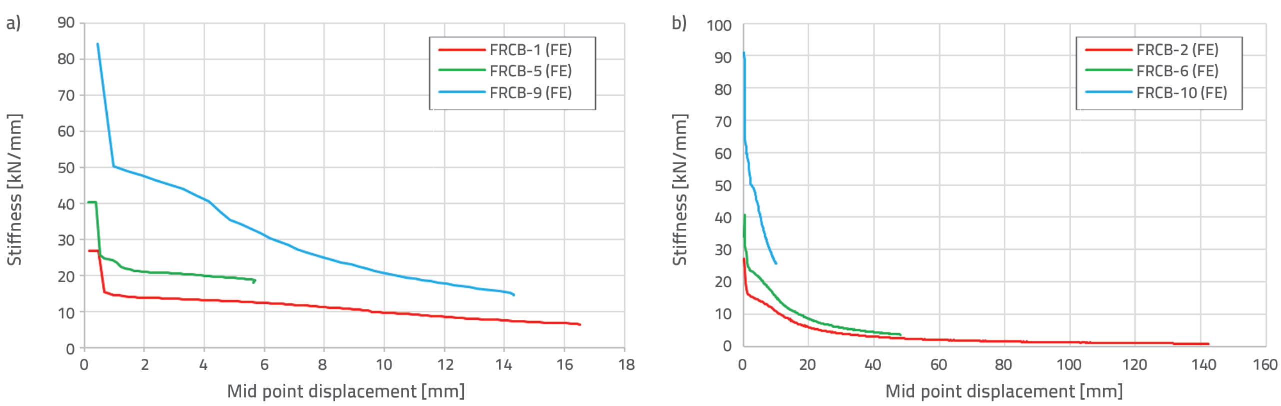

Figure 10. Stiffness-displacement curves: a) Non stirrup; b) Ø8/30 stirrup

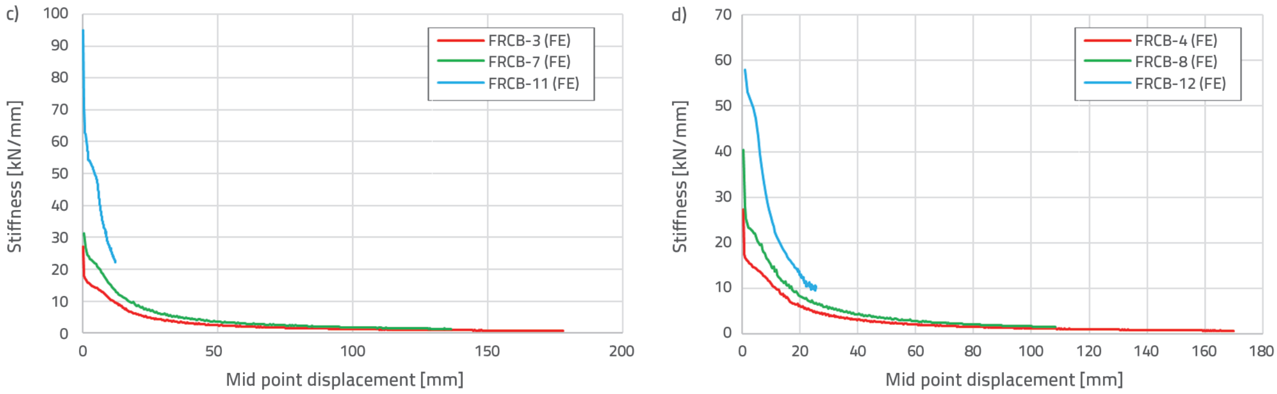

Figure 10. Stiffness-Displacement Curves: c) Ø8/15 stirrup; d) Ø8/7.5 stirrup

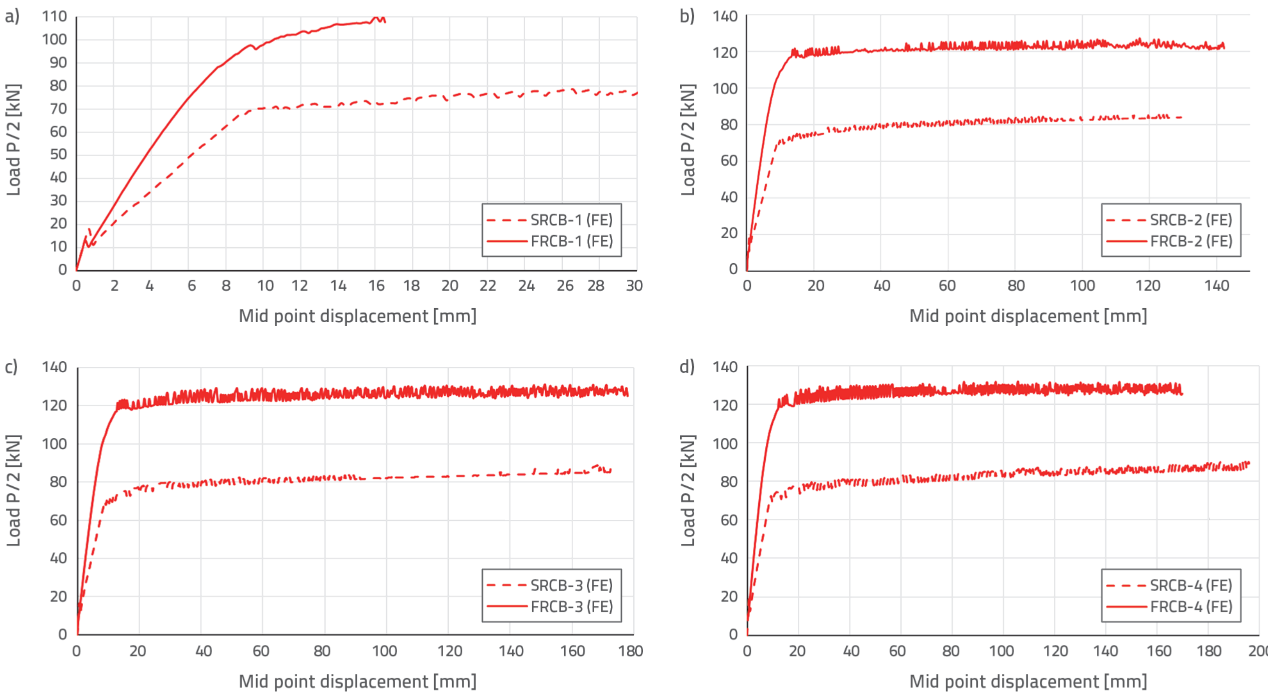

Figure 11. Comparison of load-displacement curves

support conditions. Although FRCB-1 exhibited shear behaviour before reaching the yield point, SRCB-1 first reached the yield point and then slumped owing to shear fracture. FRCB-1 exhibited a 38.1 % higher load-carrying capacity than SRCB-1. However, FRCB-1 reached a lower displacement level. FRCB-2 exhibited a 48.6 % higher load-carrying capacity than SRCB-2, FRCB-3 a 44.8 % higher load-carrying capacity than SRCB-3, and FRCB-4 exhibited a 61.2 % higher load-carrying capacity than SRCB-4.

The initial stiffness values of the specimens under fixed support conditions were considerably higher than those under simple support conditions. The stiffness graphs are shown in Figure 12. With increasing load values, the inclination angle decreases because of the decrease in stiffness. The inclination angles of the test members with fixed supports were considerably larger than those of the test members with simple supports.

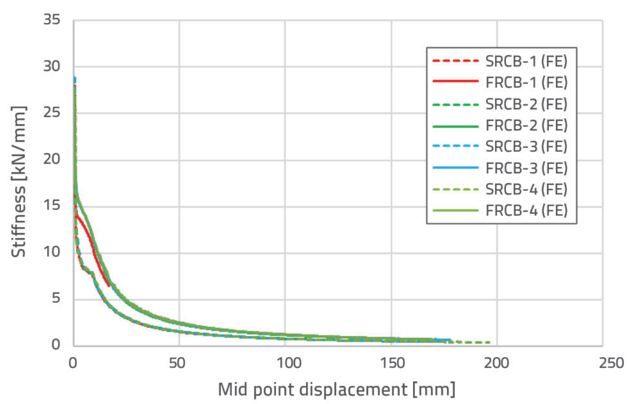

Figure 12. Comparison of stiffness

When the stress distributions of the specimens with fixed bearings were compared with those of the specimens with simple bearings, they were found to be similar in the bending regions; however, the distributions differed in the bearing regions.

4. Conclusion

The purpose of this study was to ascertain the differences in the outcomes of four-point bending tests conducted on simply supported beams and beams under fixed support conditions. For this purpose, the effects of a/d ratio, stirrup spacing, and support conditions on the behaviour of RC beams were investigated. The study was conducted experimentally and analytically.
Although a decrease in the a/d ratio increased the load-carrying capacity of the beams, it also increased the tendency of the beams to exhibit shear behaviour. The stiffness increased with a decrease in a/d ratio. However, with this decrease, the area under the load-displacement curve decreased, and the cumulative energy values consumed decreased accordingly, indicating that the ductility of the beams decreased as the a/d ratio decreased. For test members with the same a/d ratio, as the stirrup spacing decreased, the stress on the beam surface spread to all surfaces and the number of cracks increased. The formation of cracks in the beams increased the energy consumption. All specimens of the test members without stirrups failed owing to shear fracture, which shows the effect of the stirrup on the shear behaviour. When the stirrup spacing was insufficient, the test members were damaged in a sudden and brittle manner because of shear fracture before reaching flexural capacity. In specimens with low stirrup spacing, the cracks spread over the entire beam surface. The number of cracks was small in specimens with a large stirrup spacing. Therefore, specimens with a low stirrup spacing were more prone to shear behaviour. Because the test elements produced and tested in this study are on a 1/1 scale, the results of the numerical study are considered more realistic than those of other studies in the literature.
When the initial stiffness values of the elements were analysed, it was found that the elements with fixed supports were 30 % more rigid than those with simple supports. Similarly, the strength of members with built-in supports was 36 % higher than that of members with simple supports. For the test elements with fixed supports, the amount of anchorage of the beam-fixed support was determined by proportioning the moment values obtained for the beam-fixed support and the moment values obtained from the experimental study. Owing to this proportioning, the bearing areas in the experimental members without shear failure had anchorage values between 71 % and 80 %. The difference between the results of the analytical and experimental studies is because a fully anchored fixed support could not be produced in the experimental study.

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REFERENCES

[1] Altın, S., Demirel, Y.: Kesmeye Karşı Güçlendirilen Betonarme Kirişlerin Davranışı, Teknik Dergi, 108 (1997), pp. 1471-1489.

[2] Kotsovos, M.D.: Shear Failure of Reinforced Concrete Beams, Engineering Structures, 9 (1987), pp. 32-38.

[3] Kotsovos, M.D., Pavlović, M.: Size Effects in Structural Concrete: A Numerical Experiment, Computers & Structures, 64(1997) 1-4. pp. 285-295.

[4] Sahoo, D.R., Bhagat, S., Reddy, T.: Experimental study on shear-span to effective-depth ratio of steel fiber reinforced concrete T-beams, Materials and Structures, 49 (2016) 9, pp. 3815-3830.

[5] Wang, T., Dai, J.G., Zheng, J.J.: Multi-angle truss model for predicting the shear deformation of RC beams with low span-effective depth ratios. Engineering Structures, 91 (2015), pp. 85-95.

[6] Spadea, G., et al.: Structural effectiveness of FRP materials in strengthening RC beams, Engineering Structures, 99 (2015), pp. 631-641.

[7] Qeshta, I.M.I., Shafigh, P., Jumaat, M.Z.: Flexural behaviour of RC beams strengthened with wire mesh-epoxy composite, Construction and Building Materials, 79 (2015), pp. 104-114.

[8] Phuong, N.D., Mutsuyoshi, H.: Experimental study on performance of mechanical splices in reinforced concrete beams, ACI Structural Journal, 112 (2015) 6.

[9] Pawłowski, D., Szumigała, M.: Flexural Behaviour of Full-scale Basalt FRP RC Beams – Experimental and numerical studies, Procedia Engineering, 108 (2015), pp. 518-525.

[10] Ebead, U.: Inexpensive Strengthening Technique for Partially Loaded Reinforced Concrete Beams: Experimental Study, Journal of Materials in Civil Engineering, 27 (2015) 10, pp. 04015002.

[11] Dadi, K., Agarwal, P.: Effect of types of reinforcement on plastic hinge rotation parameters of RC beams under pushover and cyclic loading. Earthquake Engineering and Engineering Vibration, 14 (2015) 3, pp. 503-516.

[12] Conforti, A., et al.: Influence of polypropylene fibre reinforcement and width-to-effective depth ratio in wide-shallow beams, Engineering Structures, 88 (2015), pp. 12-21.

[13] Cansız, S.: Effect of tightening zone length of reinforced concrete beams on beam capacity, GRAĐEVINAR, 74 (2022) 10, pp. 857-868, doi: https://doi.org/10.14256/JCE.3504.2022

[14] Demir, A., Ince, Y., Altıok, T.Y.: Experimental and numerical investigation of RC beams strengthened with CFRP composites, GRAĐEVINAR, 73 (2021) 6, pp. 605-616, doi: https://doi.org/10.14256/JCE.3051.2020

[15] Vecchio, F., Balopoulou, S.: On the nonlinear behaviour of reinforced concrete frames, Can. J. Civ. Eng., 17 (1990), pp. 698-704.

[16] Altın, S., Anıl, Ö., Gökten, Y.: Betonarme Kirişlerin Kesmeye Karşı Güçlendirilmesinde Bir Kelepçe Uygulaması, Gazi Üniv. Müh. Mim. Fak. Der., 19 (2004) 4, pp. 415-422.

[17] Arslan, G., Polat, Z., Yüksek Beton Mukavemetli Betonarme Kirişlerde Uygun Sonlu Eleman Boyutları, ITU Muhendislik Dergisi, 3 (2004) 1, pp. 22-28.

[18] İnce, R., Arslan, A.: Kesme Açıklığı Kısa Kayma Donatısız Betonarme Kirişlerde Boyut Etkisi. Journal of Enginering and Environment Sciences, 24 (200), pp. 69-77.

[19] Sin, H.L., et al.: Reinforced Lightweight Concrete Beams in Flexure, ACI Structural Journal, (2011) January-February, pp. 3-12.

[20] Tokgöz, H., Dündar, B.: Kesme Yönünden Yetersiz Dikdörtgen Kesitli Betonarme Kirişlerin CFRP İle Güçlendirilerek Kesme Kapasitelerinin Arttırılması. İleri Teknoloji Bilimleri Dergisi, 3 (2014) 2, pp. 87-97.

[21] Cladera, A., Marí, A.R.: Experimental study on high-strength concrete beams failing in shear, Engineering Structures, 27 (2005) 10, pp. 1519-1527.

[22] Ersoy, G., Özcebe, G.: Betonarme/Temel İlkeler, 2016, İstanbul: Evrim Yayınevi, 816.

[23] Kim, H.S., Lee, M.S., Shin, Y.S.: Structural behaviours of deep RC beams under combined axial and bending forces, Procedia Engineering, 14 (2011), pp. 2212-2218.

[24] Kotsovos, M.D., Pavlović, M.N.: Size effects in beams with small shear span-to-depth ratios, Computers & Structures, 2004. 82 (2004) 2-3, pp. 143-156.

[25] Słowik, M.: Shear failure mechanism in concrete beams, Procedia Materials Science, 3 (2014) pp. 1977-1982.

[26] Sneed, L.H., Ramirez, J.: Influence of cracking on behaviour and shear strength of reinforced concrete beams, ACI Structural Journal, (2014) January-Februar, pp. 157-166.

[27] Yang, K.H., et al.: Shear characteristics of high-strength concrete deep beams without shear reinforcements, Engineering Structures, 25 (2003), pp. 1343-1352.

[28] Zakaria, M., et al: Shear characteristics of high-strength concrete deep beams without shear reinforcements, Journal of Advanced Concrete Technology, 7 (2009)1, pp. 79-96.

[29] Kamanlı, M., Unal, A.: Experimental study on shear behaviour of simply supported full-scaled reinforced concrete beams. 2nd International Conference on Science, Ecology and Technology-2016 (ICONSETE'2016), 2016. Barcelona/Spain.

[30] Unal, A.: Sabit dikdörtgen kesitli kirişlerin farkli mesnet koşullarinda kesme kapasitesinin araştirilmasi, Civil Engineering, 2016, Selcuk University, Konya/Turkey. p. 375.

[31] Unal, A., Kamanlı, M.: Investigation of stirrup effect on shear behaviour of fixed supported reinforced concrete beams, 2nd International Conference on Science, Ecology and Technology-2016 (ICONSETE'2016), 2016. Barcelona/Spain.

[32] Hognestad E., Hanson, N.W., McHenry, D.: Concrete stress distribution in ultimate strength design, 52 (1955) ACI J Proc.

[33] Willam, K.J.: WEP - Constitutive model for the triaxial behavior of concrete, 19 (1974), Int. Assoc. Bridg. Struct. Eng.