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Effect of Beam Reinforcement and Beam Orientation on Rotational Stiffness of Reinforced Concrete Beams

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ملخص البحث :

جساءة الدوران للكمرات هى احد خصائصها المهمه لانها تؤثر مباشرة على العزوم عند نهايات الكمرات وكذلك تؤثر فى توزيع العزوم فى المنشأت الغير محددة استاتيكيا. جساءة الدوران تعرف بالمعادلة (M/Ө) حيث Ө هى زاوية الدوران الناتجه من تطبيق عزم مقداره M. عند اتصال مجموعة من العناصر الانشائية فى وصله جاسئة فان توزيع العزوم بين هذة العناصر يعتمد على جساءة الدوران لكل عنصر، فالعنصر الاقوى فى الجساءة ينتقل له قيمه اكبر من العزوم. لذلك يعتبر تقييم جساءة الدوران عند نهايات الكمرات بدقة من العوامل المهمة لحساب العزوم للمنشآت الغير محددة إستاتيكياً. هناك العديد من العوامل التى تؤثر على جساءة الدوران للكمرات الخرسانية المسلحة مثل نسبة حديد التسليح العلوي عند الإرتكاز وكذلك زاوية الإنحراف بين بحور الكمرات فى المسقط الافقى. تم الاختبار المعملى على كمرات خرسانية مسلحة مكونة من بحرين محملة في منتصف البحر بحمل مركز. تم تحضير و إختبار ستة عينات مقسمة الى مجموعتين، المجموعة الأولى مكونة من ثلاث عينات بنسب حديد مختلفة (0.654 و1.09 و1.37)%. اما المجموعة الثانية فهى ايضا مكونة من ثلاث عينات بإنحرافات أفقية مختلفة بين البحرين (15و30و60)°. عينات المجموعة الأولى تم اعدادها لدراسة تاثير نسبة التسليح العلوي فوق نقطة الإرتكاز الوسطى على جساءة الدوران عند هذا الإرتكاز. والمجموعه الثانية تم اعدادها لدراسة تاثير الإنحراف الأفقي لبحور الكمرات على جساءة الدوران للكمرات الخرسانية المسلحة. بعد تحليل نتائج البرنامج العملى تبين أن نسبه التسليح لها تاثير واضح على قيمة دوران الكمرات عند الإرتكاز الأوسط. فكلما زادت نسبة التسليح قل الدوران. أما قيمة الإنحراف الأفقي لبحور الكمرات فكان لها تاثير كبير على زيادة زاويه الدوران عند الإرتكاز الأوسط للكمرات ولكنه كان له تأثير أكبر على جساءة الدوران عند الإرتكاز حيث إدى إلى خفض قيمتها.

ABSTRACT ***:*** The rotational stiffness at the beam ends is a very important characteristic because it has a direct effect on the end moments and therefore will significantly affect the moment distribution in indeterminate structures. For a group of elements connected at a joint, the bending moment distributed to any element is dependent on the element's rotational stiffness. The element with the larger stiffness will attract higher moment values. There are many factors that affect the rotational stiffness at the beam ends such as the amount of steel reinforcement over the interior support and the relative plan orientation of the beam spans. An experimental program was conducted to study these two parameters on 2-spans beams. Six specimens divided into two groups were constructed and tested up to failure. The first group consisted of three specimens with different top steel ratio at the middle support and was prepared to investigate the effect of steel ratio on the rotational stiffness. The second group consisted of three specimens with different plan orientation angle and was prepared to study the effect of beam orientation on the rotational stiffness. The results (cracks, strains, deflections and rotations) were measured and recorded at each load step until failure. From the presentation and analysis of the experimental results it was concluded that increasing the top steel ratio at the inner support had a significant effect in decreasing the rotation near the support, increasing the failure load, increasing the moment capacity over the support and increasing the rotational stiffness of the beam.

The plan orientation angle had a slight effect on the load capacity of the beam but its effect on the stiffness was pronounced.

KEYWORDS - R.C beams, rotational stiffness, flexural rigidity, beam orientation.

I. INTRODUCTION

Reinforced concrete beams are important elements in reinforced concrete structures. They are used to support applied loads along the span and transfer them to the nearest column or beam. Through their rigid connection with columns, they can also play a role in providing horizontal stability. The rotational stiffness at the beam ends is a very important characteristic because it has a direct effect on the end moments and therefore will significantly affect the moment distribution in indeterminate structures. Rotational stiffness is defined as (M/ϴ), where ϴ is the rotation produced by the applied moment (M). For a group of elements connected at a joint, the bending moment distributed to any element is dependent on the element's rotational stiffness. The element with the larger stiffness will attract higher moment values. One of the most famous methods to analyze indeterminate structures, the moment distribution method, is mainly based on this principle. In any method of analysis of indeterminate structures, the rotational stiffness at the joints is a major factor affecting the distribution of moment. Therefore the accurate evaluation of the rotational stiffness is very important to produce an accurate and realistic bending moment diagram for indeterminate structures. Reinforced concrete structures are highly non-linear structures because they normally crack under normal conditions and their behavior is defined by the interaction between the cracked concrete section and the imbedded steel reinforcement. Therefore, evaluating the rotational stiffness of the reinforced concrete beams is not a simple analytical task. There are many factors that affect the rotational stiffness at the beam ends such as the amount of steel reinforcement and the relative plan orientation of the beams. In this research, these two factors are studied experimentally for a two-span beam subjected to statically applied concentrated loads at mid span.

II. Background

The influence of redistribution of design bending moments on the performance of continuous reinforced concrete beams was studied by Mattock. A. H.[1] and Alkersh.M. A.[2]. The study revealed that the redistribution of bending moment was taking place in the working load range although the steel stresses were below the yield point stress. Redistribution of moment, however, is directly proportional to the beam rotational stiffness and moment-rotation characteristics. There are many factors affecting the moment-rotation relationship such as concrete compressive strength Alva.G. M, et al. [3], slippage of beam reinforcement bars and cracks propagation in plastic hinge region Alva.G.M and Eldebs.A. L. [4]. There are several parameters affecting the rotational stiffness of beams. Amanat K.M. and Enam.B.[5] investigated the rotational characteristics of a typical exterior R.C joint. The effect of beam depth, beam bottom steel ratio and the column steel ratio on the rotational stiffness of the beam was studied using numerical model. The study revealed that the increase of beam depth increased the rotational stiffness of the beam but in a non-linear manner. In addition, beam bottom steel ratio also produced the same effects. Column reinforcement had some influence on the rotational characteristics of the beam.

Essa. A.S.[6] studied experimentally the behavior and rotational stiffness of the reinforced concrete beam-column connections. The program included testing of nine specimens. The results of this study showed that in the elastic zone the rotational stiffness of the beam-column joint is not influenced by the variation of reinforcement ratios. The main parameters affecting the rotational stiffness in the elastic zone were the dimensions of the beam and the column. Beyond the elastic zone and with the spread of cracks in the joint, the behavior of beam-column connection was significantly influenced by the top steel reinforcement ratio. The increase of the top steel ratio has increase the rotational stiffness of the beam-column joint. Also, extending the beam top steel inside the column increased the rotational stiffness of the beam-column connections. The rotational stiffness of the beam was also increased with the increase of column dimensions. In case when the depth of the beam was bigger than the column width, the plastic hinge was formed in the column, and cracks also propagated in the column. Effect of transverse reinforcement on the joint stiffness was studied by Joh.O. et al. [7]. The results of experiments showed that heavy transverse joint reinforcement reduced the slippage of the longitudinal beam bars in the joint and enhanced the joint stiffness after cracking. In addition, adding diagonal bars to the joint was investigated by Urukap.T.H. et al. [8]. Effect of cantilever beam inclination angle on the behavior of the beams was studied by Ali.M. A. [9].

The effect of top steel reinforcement over the support and the plan orientation angle of beams on the rotational stiffness have not been sufficiently studied in the literature. In this research, these two parameters are investigated experimentally for a two spans beam loaded statically by concentrated loads at mid span.

III. experimental program

The test specimens consisted of beams with two equal spans of length (1200mm) and cross section dimensions of (180mm x 200mm). The specimens were divided into two groups: the first group was used to investigate the effect of the top reinforcement ratio over the middle support, while the second group was used to study the effect of the orientation angle between the two spans. In the first group, the steel ratio of the top reinforcement over the middle support was varied from a ratio of 0.654% to 1.37%. The second group consisted of three specimens with variable orientation angles, (inclination in plan view), of 15, 30 and 60 degrees.

To study the flexural behavior of the beams it was necessary to avoid shear failure. Therefore, the amount of shear reinforcement was chosen to provide a shear capacity that exceeded the flexural capacity of the beams. This was accomplished by using Ø8 stirrups with 3 branches spaced at 70 mm. The targeted compressive strength of concrete, F_{cu}, for all specimens was 40 N/mm2. Details of the tested specimens are as shown in tables (Table 1), (Table 2).

Table 1 : Details of group1 specimens.

Groups	Beam	Beam section(mm)	Longitudinal R.F.T.	
			As$'$(mm^2)(ρ%)	As(mm^2) (ρ%)
Group 1	B11	180x200	3ϕ10 (0.654%)	3ϕ10 (0.654%)
	B12	180x200	5ϕ10 (1.09%)	3ϕ10 (0.654%)
	B13	180x200	3ϕ12+2 ϕ10 (1.37%)	3ϕ10 (0.654%)

Table 2 : Details of group2 specimens.

Groups	Beam	Beam section(mm)	Longitudinal R.F.T.		Beam orientation(°)
			As′(mm2)	As(mm2)	
Group 2	B21	180x200	3ϕ10	3ϕ10	15°
	B22	180x200	3ϕ10	3ϕ10	30°
	B23	180x200	3ϕ10	3ϕ10	60°

As′ = Area of steel over the mid support, As = bottom steel, ρ=steel ratio

Three different parameters were measured during loading, and the values were recorded for the corresponding loading values. The three parameters were the deflections, the strains in the steel reinforcement and the rotations. Linear Variable Displacement Transducers (LVDT) with an accuracy of 1/100-mm were used for measuring deflection, electrical strain gauges (type FLA-6-11-1L) were used for measuring steel strains and digital inclinometer gauge with resolution of 0.05° and accuracy 0.2° was used to measure the rotation of the beam near the support.

Figure 1 shows the concrete specimens after curing. Figures 2 and 3 show the photos of the loaded straight beam (Group 1), and a loaded inclined beam (Group 2), respectively.

I. EXPERIMENTAL RESULTS

The results (cracks, strains, deflections and rotations) were measured and recorded at each load step until failure. The first group which consisted of three specimens studied the effect of the negative steel ratio over the central support of the two spans beam. The second group also consisted of three specimens and studied the effect of the plan orientation angle between the two spans. Figures (4) and (5) show typical crack patterns after failure for the first and the second group, respectively. The figures show that the cracks appeared near the top of the beam at the mid support and at the bottom of beam at mid span. The cracks were nearly vertical typical of flexural cracks occurring due to steel yielding. No inclined shear cracks were observed indicating that the mode of failure was a flexural mode of failure.

Fig.1 Test specimens after curing.

Fig.2 General setup of group1 specimens.

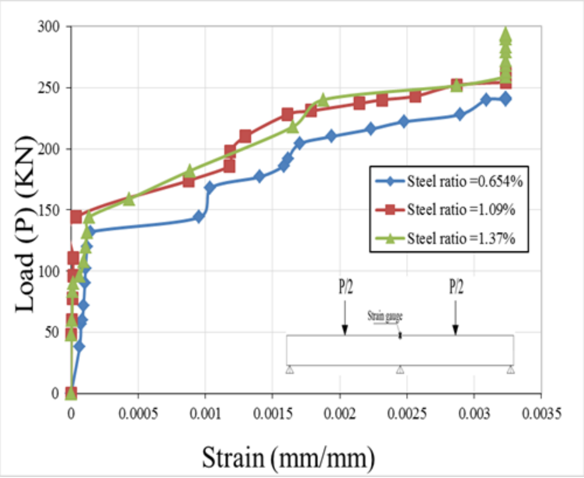
Fig.3 General setup of group2 specimens.

Fig.4 Mode of failure for group 1.

Fig.5 Mode of failure for group 2.

The relation between the vertical load and the measured steel strain is presented in figure (6) and (7) for group (1) and (2), respectively. The shape of the relation was similar for the all beams starting with a linear relation with a steep slope, followed by a flat curve typical of the steel stress strain curve. The value of the maximum steel strain for all specimens was nearly the same. A well-defined pattern for the relation between the steel ratio or the orientation angle and the steel strain could not be noticed.

The relation between the vertical load and the measured rotation is presented in figure (8) and (9) for group (1) and (2), respectively.



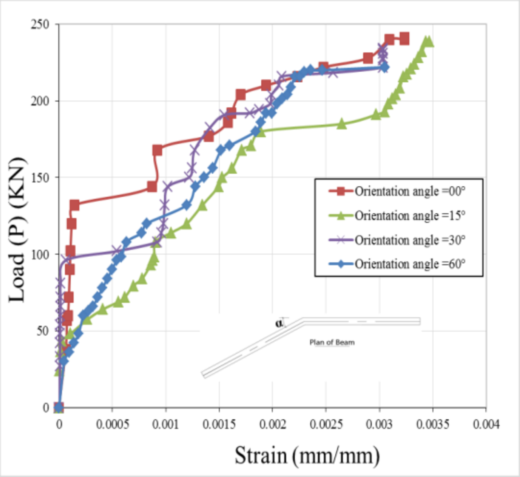
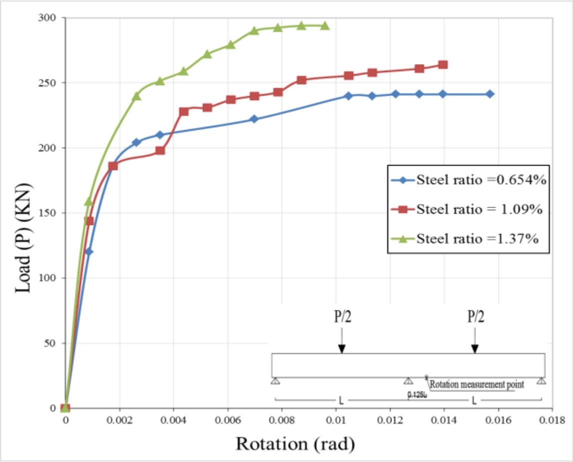


Fig.6 Load-Strain curve for group 1.

Fig.7 Load-Strain curve for group 2.



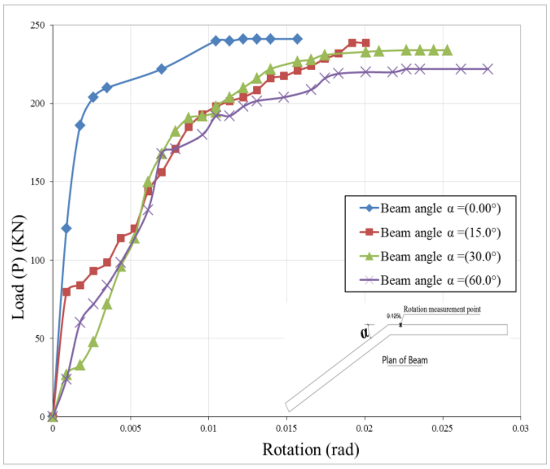
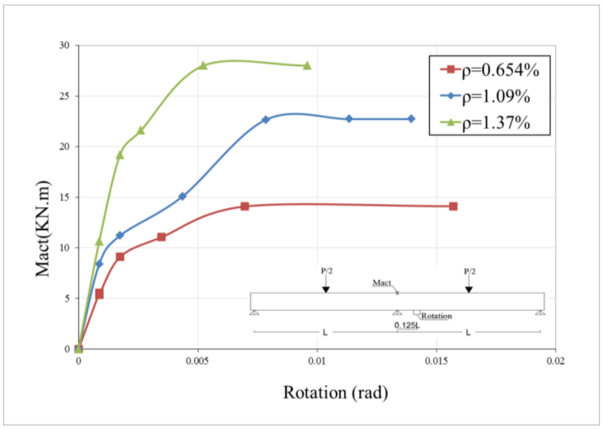


Fig.8 Load-Rotation curve for group 1. Fig.9 Load-Rotation curve for group 2.

Figure (8) shows that the beams with higher steel ratio at the support showed a decrease in the final rotation at failure. The figure also reveals that the critical load at which the rotation started increasing in a non-linear manner was about 180 KN for beams (B11) and (B12) compared to a much higher value of about 240 KN for beam (B13) with the higher steel ratio. The value of the failure load also increased as the steel ratio of the support increased. Figure (9) shows that the increase of beam orientation angle leads to an increase in the beam maximum rotation and a decrease in the failure load.

The actual negative bending moment was obtained using the steel stress calculated from the actual steel strain recorded during the experiment using the installed strain gauge. The relation between the actual bending moment and the measured rotation is presented in figure (10) and (11) for group (1) and (2), respectively.



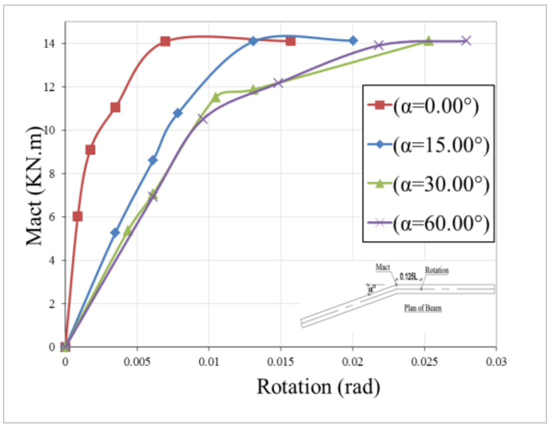


Fig.10 Moment-Rotation curve for group 1. Fig.11 Moment-Rotation curve for group 2.

Figure (10) showed similar behavior for the three beams. The moment-rotation curves in the figures could be divided into three parts, the first part represented a linear relationship with a high rotational stiffness (i.e. high slope where the rate of change of moment with respect to the change in rotation was high). The second part was formed of a relation with a considerably lower rotational stiffness. In the third part, the relation was nearly horizontal (i.e. The moment didn't increase with the increase of rotation indicating a plastic hinge).

The figure shows that the ratio of steel had a significant effect on the moment-rotation relationship. The increase of the top steel ratio over the support has caused the first linear section of the curve to increase. The moment capacity was also increased with the increase of steel ratio but the maximum rotation at failure decreased producing a less ductile beam. Increasing the steel ratio from 0.654% to 1.37% (a 109% increase) increased the calculated actual moment by 98.44% and decreased the rotation at failure by 38.88%.

Figure (11) showed similar behavior for the three beams, and were also similar to the straight beams. The relation could also be divided into three parts similar to the discussion of group I beams. This figure also shows that beams bearing different orientation angles behave in a different manner. Although the differences in the failure loads were small (not exceeding 9%), and the maximum moments attained were equal, the beams showed pronounced difference in stiffness especially in the initial phase. The slope of the linear section of the relation was much higher for the straight beam as compared to the beams with orientation angles as shown in the figure.

The relation between experimental rotational stiffness and the steel ratio over the middle support is presented in figure (12). The relation between the experimental rotational stiffness and beam plan orientation is presented in figure (13). The experimental rotational stiffness, (Km), was calculated using the following equation:

$$Km = Mact./\Theta \qquad (1)$$

Where:

Mact. = the actual bending moment over the support.

Θ = the measured angle of rotation near the middle support.

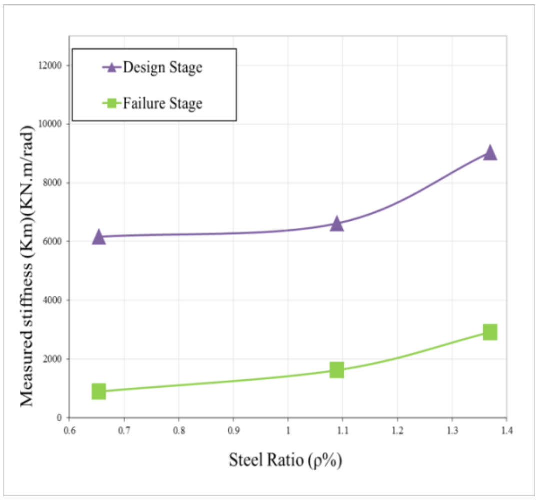


Fig.12 Steel ratio-Stiffness for group1

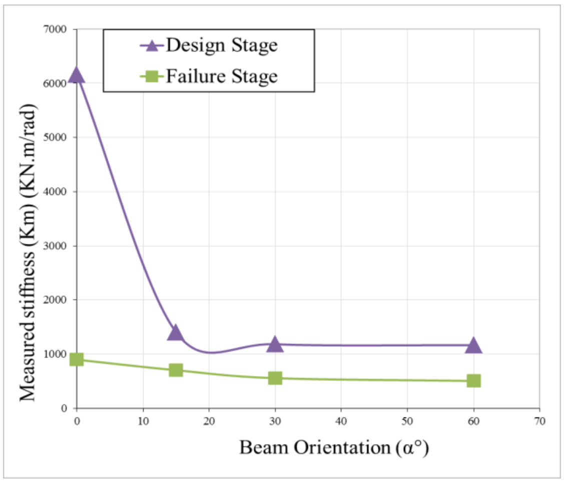


Fig.13 Beam orientation-Stiffness for group2.

Figure (12) shows the relation between steel ratio and the rotational stiffness of beams at 70% of failure load (approximately design stage), and at the failure load stage. The figure shows that the increase of the top steel ratio over the support was associated with an increase in the rotational stiffness. At 70% of failure load, the rotational stiffness was high since the rotation was small and the stresses at the section were low. As the failure stage was approached, the rotational stiffness was considerably decreased, due to the increase in strains and the corresponding increase in rotation. As the steel ratio increased from 0.654% to 1.37%, the rotational stiffness increased by 46.58% at 70% of the failure load and by 224.7 % at the failure load stage, i.e. the effect of the steel ratio on the rotational stiffness was more pronounced as the load increased.

Figure (13) shows the relation between orientation angle and the rotational stiffness of beams at 70% of failure load (approximately design stage), and at the failure load stage. The figure shows that the increase of the orientation angle from 0 to 30° caused a decrease in the measured stiffness. The difference in the measured stiffness between the 30° and 60° orientation angles was nearly negligible. The decrease of stiffness in the design phase was very large as the orientation angle changed from 0 to 15°, but was much smaller as the angle changed from 15° to 30°. The change in stiffness at the failure stage was much smaller if compared to the design stage. At the failure stage, increasing the beam orientation angle from (0.00°) to (15.00°), (30.00°) and (60.00°) led to a decrease in the rotational stiffness by 21.6%, 37.9% and 43.8% respectively.

II. Conclusions

The experimental program showed that the ratio of the top steel reinforcement in the central support of a continuous reinforced concrete beam had a significant effect on the moment-rotation relationship. Increasing the steel ratio produced a less ductile beam with a decreased maximum rotation, higher failure load and higher measured moment value at failure. The rotational stiffness of the beams at the central support also increased as the ratio of the top steel increased.

The experimental work also demonstrated that the beams bearing an orientation angle behaved in a different manner than the straight beam. The failure load was slightly lower, but the measured moment at failure was nearly equal. The cracking moment was affected by the orientation angle but no clear pattern was identified. The rotational stiffness was also affected by the orientation angle. Increasing the orientation angle caused the rotational stiffness of the beams at the middle support to decrease, and the maximum rotation at failure to increase.

It was also noticed that the rotational stiffness observed at 70% of the failure load was considerably higher than the rotational stiffness observed as failure was approached.

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