Numerical investigation of shear reinforcement effects on the flexural behavior of reinforced concrete beams

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Abstract: The aim of this article is to study the effects of lateral reinforcement on the flexural behaviour of Straight Reinforced Concrete (RC) Beam by Finite Element Method (FEM). Three-dimensional nonlinear finite element analyses was performed for simply and fixed supported beams utilizing computer program called NFHCBSL, this program incorporates 20-node isoparametric brick element that is used to represent the concrete elements while reinforcing bars are idealized as axial members embedded within the concrete elements without any relative displacement between them. Different flexural reinforcement ratios, stirrups spacing, depth to width ratios (h/b), and shear span to depth ratios (a/h) have been studied. The failure of all specimens is designed to be by flexure. The results have shown that the most increments in ultimate load with increasing shear reinforcement were found for ratios of $\rho_{\text{prov}}/\rho_{\text{max}}$ larger than 80% for h/b less than or equal to 2, while the increments were near to 9% when the stirrups increased by 100%. Also, for h/b is equal to 2.5 the optimal efficiency of stirrups on the ultimate load was at $\rho_{\text{prov}}/\rho_{\text{max}}$ equal to 43. The increments in the ultimate loads were 20% and 33% when the stirrups increased by 50% and 100% respectively.

Key words: Straight reinforced concrete beam; shear reinforcement spacing; flexural reinforcement ratio; ductility

1. Introduction
The shear reinforcement in reinforced concrete structures gives resistance for shear, prevents the longitudinal reinforcement from moving during construction, prevents buckling for the compression reinforcement and confines the concrete within the core. Okamura and Higai [1] presented analytical study for shear strength of reinforced concrete beams with simple equation expressed by concrete strength, reinforcement ratio and effective depth in a cumulative form. Pam et al. [2] tested a number of singly reinforced concrete beams made of normal- and high-strength concretes under monotonically increasing loads to study their flexural behavior and to compare the flexural ductility of normal- and high-strength concrete beams. The ductility of members does not only depend on the strength of concrete, but also it depends on the type of member, the loading arrangement and the reinforcement layout. The results have showed that the use of high-strength concrete in place of normal strength concrete has increased the bending strength of the beam.

Piyamahant [3] showed that the reinforced concrete structures should have shear reinforcement equal to the minimum requirement specified by the code. The analytical results have been demonstrated that the amount of shear reinforcement of 0.2% is the appropriate. The paper concluded that small amount of shear
reinforcement is sufficient to improve the shear carrying capacity. The study focused on the applicability of the superposition method that used in predicting shear carrying capacity of reinforced concrete beam with a small amount of web reinforcement when the shear span to depth ratio is equal to three. Shah and Ahmad [4] studied the effect of longitudinal steel and shear span to depth a/d ratios of high strength concrete beams. It has been shown that the failure of the beams with lower values of longitudinal steel is mainly due to flexure cracks and the shear reinforcement plays no or very little role in improving the shear capacity or restricting the beam failure.

Saatci and Vecchio [5] tested eight reinforced concrete simply supported beam specimens, four pairs, were tested under free-falling drop-weights, impacting the specimens at the mid-span. All specimens had identical longitudinal reinforcement, but varying shear reinforcement ratios, to investigate the effects of shear capacity on the impact behavior. Four additional specimens were cast to determine the static behavior of the specimens tested under impact loading. The results show that the shear characteristics of the specimens played an important role in their overall behavior. Specimens with higher shear capacity were able to sustain more impacts and absorb more energy, whereas the ones with lower shear capacity suffered extensive damage under the same or smaller impact loads.

Słowik [6] showed that the shear span to depth ratio a/d has the main effect on the shear strength in concrete members reinforced longitudinally without shear reinforcement. The performed tests have been shown that the effective length-to-depth ratio has effects on the shear resistance mechanism and the ultimate shear capacity. The size effect is not only the depth of the member but also all dimensions: depth, effective length and width have considered effect. The main aim of the study is to investigate the effects of lateral reinforcement on the flexural behaviour of reinforced concrete beam for different ratios of flexural reinforcement and span to depth ratio. For the purpose of investigating about the effects of lateral reinforcement on the behaviour and load carrying capacity of RCB as well as to provide a data base for numerical analysis, a total number of fifteen samples was collected from previous work [7].

2. Finite element modelling
The analysis was performed by an application of a computer programs Nonlinear Finite element analysis of Horizontally Curved Beam under Static Load (NFHCBSL) [8] presented by Al-Mutairee [9] adopted in this research, this program has been used by many researchers [10–12].

2.1. Reliability of program
For the purposes of investigating about the effects of lateral reinforcement on the behavior and the load carrying capacity of RCB as well as to provide a data base for numerical analysis, a total number of fifteen samples was presented in this study. The main goal was to evaluate the effects of shear reinforcement (confinement) on the behavior of RCB. Furthermore, multiple tests were conducted on the materials used to evaluate the mechanical properties such as the tensile strength of the steel bar. Concrete was also tested at age 28day to evaluate its strength under both compression and tension stresses. All properties of materials and the parameters adopted in the analysis are detailed in table 1. The loads applied as a non-uniform increments and as detailed in table 2. A convergence study of beams was done including six different meshes involving a total of 54, 72, 90, 108, 126, and 144 elements. The results show that the difference between any successive meshes decreased until it is reached to 1% between 108 element and 126 element meshes. Thus the mesh of 108 is adopted in the analyses.
Table 1. Properties of materials and parameters adopted in the analysis.

| Materials Properties                                      | Value                      |
|-----------------------------------------------------------|----------------------------|
| The compressive strength of concrete                      | $f'c = 27$ MPa             |
| The yield strength for longitudinal reinforcements        | $f_y = 573.3$ MPa for (Ø10) |
|                                                            | $f_y = 561$ MPa for (Ø5)   |
| The yield strength for stirrups reinforcements            | $f_y = 561$ MPa for (Ø5)   |
| The modulus of elasticity of concrete                     | $E_c = 24.4$ GPa          |
| The tensile strength of concrete                           | $f_t = 3.2$ MPa            |
| Concrete:                                                 | $\nu = 0.2$, $\varepsilon_u = 0.003$ |
| Reinforcement:                                            | $\nu = 0.0$, $\varepsilon_u = 0.12$ for longitudinal reinforcement and 0.2 for stirrups |
| The modulus of elasticity of steel                         | $E_s = 200$ GPa            |

| Parameters                                                | Value                      |
|-----------------------------------------------------------|----------------------------|
| $\alpha_1$                                                | $40$                        |
| $\alpha_2$                                                | $-0.1$                      |
| $\gamma_1$                                                | $10$                        |
| $\gamma_2$                                                | $0.5$                       |
| $\gamma_3$                                                | $0.2$                       |
| CP                                                        | $0.3$                       |

Note: Tolerance is variable and it ranges from 0.6% to 1%.

Table 2. The incremental analytical scheme of applying the load of beams.

| Number of Increments | $\leq 20$ | $\geq 21$ | $\geq 50$ |
|----------------------|-----------|-----------|-----------|
| The Applied Load $\Delta P$ (kN) | 3         | 2         | 1         |

2.2. Number of loaded and supported nodes

The number of nodes for each support and each load were five nodes as shown in figure 1.

Figure 1. Finite Element Mesh of 108 Brick Element of B11.

The ultimate loads of the fifteen samples obtained from experimental tests [7] and numerical results are listed in table 3. From comparison between numerical and experimental loads, maximum difference between loads was less than 13% for the specimen B27.
2.3. Effects of stirrups on the flexural behavior of RC simply supported beams for different ratios of longitudinal reinforcement ($\rho_{\text{provid}}/\rho_{\text{max}} = 0.667$)

Five values of $\rho_{\text{provid}}/\rho_{\text{max}}$ have been selected for each group to investigate the effects of stirrups. The dimension of beams as detailed in table 4 with three values of spacing between stirrups for each case of ratio.

2.3.1 Behavior of beams of first group ($h/b=1.5$).

Table 3 shows the effects of variation of $\rho_{\text{provid}}/\rho_{\text{max}}$ from 0.29 to 0.9 on the ultimate load with three values of spacing between stirrups. The results proved that when the ratio of $\rho_{\text{provid}}/\rho_{\text{max}}$ is equal to 0.29 and when the spacing decrease from 100mm to 50mm the increment in ultimate load was equal to 5%. While the increments in ultimate load, due to duplicate stirrups were 3.92%, 8.94%, 5.33%, and 10.23% for ratio of $\rho_{\text{provid}}/\rho_{\text{max}}$ is equal to 0.45, 0.58, 0.77, and 0.9 respectively. While the increment from experimental work was 16.53%. These results show that the effectivity of stirrups approximately increases with ratio $\rho_{\text{provid}}/\rho_{\text{max}}$.

### Table 3. Section geometry, reinforcement details, experimental and analytical results of tested simply supported beams.

| Beam Name | Dimension (mm) | Longitudinal Reinforcement | Shear Reinforcement | Ratio of $\mu_{\text{u}}/\mu_{\text{a}}$ | Ultimate Load (KN) | $P_{\text{exp}}$ | $P_{\text{theo}}$ |
|-----------|----------------|----------------------------|---------------------|-----------------|---------------------|----------------|----------------|
| B11       | h=240          | b=160                      | 5010                | 9               | 6                   | 0.67           | 2.78          |
| B12       | h=160          | b=1.5                      | 4.5                 | 100             | 14                  | 0.67           | 2.08          |
| B13       | h=320          | b=160                      | 3010                | 14              | 10                  | 0.67           | 2.08          |
| B21       | h=160          | b=2                        | 6010                | 12              | 8                   | 0.67           | 2.08          |
| B22       | h=320          | b=2                        | 6010                | 12              | 8                   | 0.67           | 2.08          |
| B23       | h=160          | b=2                        | 6010                | 12              | 8                   | 0.67           | 2.08          |
| B24       | h=160          | b=2                        | 6010                | 12              | 8                   | 0.67           | 2.08          |
| B25       | h=160          | b=2                        | 6010                | 12              | 8                   | 0.67           | 2.08          |
| B26       | h=160          | b=2                        | 6010                | 12              | 8                   | 0.67           | 2.08          |
| B27       | h=160          | b=2                        | 6010                | 12              | 8                   | 0.67           | 2.08          |
| B28       | h=160          | b=2                        | 6010                | 12              | 8                   | 0.67           | 2.08          |
| B29       | h=160          | b=2                        | 6010                | 12              | 8                   | 0.67           | 2.08          |
| B30       | h=160          | b=2                        | 6010                | 12              | 8                   | 0.67           | 2.08          |
| B31       | h=160          | b=2                        | 6010                | 12              | 8                   | 0.67           | 2.08          |
| B32       | h=160          | b=2                        | 6010                | 12              | 8                   | 0.67           | 2.08          |
| B33       | h=160          | b=2                        | 6010                | 12              | 8                   | 0.67           | 2.08          |

2.4. Effects of stirrups on the flexural behavior of RC simply supported beams for different ratios of longitudinal reinforcement for $(M_{\text{u}}/V_{\text{a}} = 0.667)$
Table 4. Effect of $\rho_{\text{provided}}/\rho_{\text{max}}$ ratio on the ultimate load of beams of the first group.

| Longitudinal reinforcement | $\rho_{\text{provided}}/\rho_{\text{max}}$ ratio | Spacing between stirrups (mm) | Ultimate Load (KN) | Increment in ultimate load% |
|----------------------------|-----------------------------------------------|------------------------------|---------------------|-----------------------------|
| 1Ø10+2Ø6                   | 0.29                                          | 100                          | 80                  | ---                         |
|                            |                                               | 67                           | 80                  | 0                           |
|                            |                                               | 50                           | 84                  | 5                           |
| 2Ø10+3Ø5                   | 0.45                                          | 100                          | 102                 | ---                         |
|                            |                                               | 67                           | 103                 | 1                           |
|                            |                                               | 50                           | 106                 | 4                           |
| 3Ø10+2Ø5                   | 0.58                                          | 100                          | 123                 | ---                         |
|                            |                                               | 67                           | 127                 | 3                           |
|                            |                                               | 50                           | 134                 | 9                           |
| 1Ø16+2Ø10                  | 0.77                                          | 100                          | 150                 | ---                         |
|                            |                                               | 67                           | 155                 | 3                           |
|                            |                                               | 50                           | 158                 | 5                           |
| 5Ø10                       | 0.9                                           | 90                           | 152                 | ---                         |
|                            |                                               | 60                           | 160                 | 5                           |
|                            |                                               | 45                           | 168                 | 10                          |
| 5Ø10                       | 0.9*                                          | 90                           | 141.6               | ---                         |
|                            |                                               | 60                           | 156.3               | 10                          |
|                            |                                               | 45                           | 165.0               | 17                          |

Note: * means experimental work.

2.3.2 Behavior of beams of second group ($h/b=2.0$).

Table 5 shows the effects of variation of $\rho_{\text{provided}}/\rho_{\text{max}}$ from 0.3 to 0.88 on the ultimate load with three values of spacing between stirrups. The results showed that when the ratio of $\rho_{\text{provided}}/\rho_{\text{max}}$ equal to 0.3 and spacing decrease from 140mm to 70mm the increment in ultimate load was equal to 3.03%. While the increments in ultimate load, due to duplicate stirrups were 4.35%, 4.49%, 4.51%, and 8.14% for ratio of $\rho_{\text{provided}}/\rho_{\text{max}}$ is equal to 0.48, 0.6, 0.75, and 0.88 respectively. While the increment from experimental work was 2.13% for $\rho_{\text{provided}}/\rho_{\text{max}}$ equal to 0.47.

Table 5. Effect of $\rho_{\text{provided}}/\rho_{\text{max}}$ ratio on the ultimate load of beams of the second group.

| Longitudinal reinforcement | $\rho_{\text{provided}}/\rho_{\text{max}}$ ratio | Spacing between stirrups (mm) | Ultimate Load (KN) | Increment in ultimate load% |
|----------------------------|-----------------------------------------------|------------------------------|---------------------|-----------------------------|
| 2Ø10+2Ø5                   | 0.3                                           | 140                          | 165                 | ---                         |
|                            |                                               | 93                           | 165                 | 0                           |
|                            |                                               | 70                           | 170                 | 3                           |
| 2Ø12+1Ø10                  | 0.48                                          | 140                          | 184                 | ---                         |
|                            |                                               | 93                           | 186                 | 1                           |
|                            |                                               | 70                           | 192                 | 4                           |
| 2Ø14+1Ø10                  | 0.6                                           | 140                          | 245                 | ---                         |
|                            |                                               | 93                           | 251                 | 2                           |
|                            |                                               | 70                           | 256                 | 4.5                         |
| 2Ø16+1Ø10                  | 0.75                                          | 100                          | 288                 | ---                         |
|                            |                                               | 67                           | 299                 | 4                           |
|                            |                                               | 50                           | 301                 | 4.5                         |
| 2Ø16+2Ø10                  | 0.88                                          | 80                           | 307                 | ---                         |
|                            |                                               | 53                           | 321                 | 4.5                         |
2.3.3 Behavior of beams of third group \((h/b=2.5)\).

Table 6 shows the effects of variation of \(\rho_{\text{provided}}/\rho_{\text{max}}\) from 0.3 to 0.9 on the ultimate load with three values of spacing between stirrups. The results showed that when the ratio of \(\rho_{\text{provided}}/\rho_{\text{max}}\) equal to 0.3 and spacing decrease from 130mm to 65mm the increment in ultimate load was equal to 7.84%. While the increments in ultimate load, due to duplicate stirrups were 32.78%, 3.82%, 5.79%, and 9.31% for ratio of \(\rho_{\text{provided}}/\rho_{\text{max}}\) is equal to 0.43, 0.6, 0.8, and 0.9 respectively. While there is no increment from experimental work where it was -1.40% for \(\rho_{\text{provided}}/\rho_{\text{max}}\) equal to 0.61. It is important to note that for \(h/b\) is equal to 2.5 the optimal efficiency of stirrups was at \(\rho_{\text{provided}}/\rho_{\text{max}}\) is equal to 0.43.

| Longitudinal reinforcement | \(\rho_{\text{provided}}/\rho_{\text{max}}\) ratio | Spacing between stirrups (mm) | Ultimate Load (KN) | Increment in ultimate load% |
|---------------------------|----------------------------------|------------------|-----------------|-----------------------------|
| 1Ø10+2Ø6                  | 0.3                              | 130              | 102             | ---                         |
|                           |                                  | 86.7             | 104             | 1.96                        |
|                           |                                  | 65               | 110             | 7.84                        |
| 2Ø10+2Ø5                  | 0.43                             | 130              | 122             | ---                         |
|                           |                                  | 86.7             | 147             | 20.49                       |
|                           |                                  | 65               | 162             | 32.78                       |
| 1Ø12+2Ø10                 | 0.6                              | 130              | 157             | ---                         |
|                           |                                  | 86.7             | 161             | 2.55                        |
|                           |                                  | 65               | 163             | 3.82                        |
| 1Ø16+2Ø10                 | 0.8                              | 90               | 190             | ---                         |
|                           |                                  | 60               | 191             | 0.53                        |
|                           |                                  | 45               | 201             | 5.79                        |
| 2Ø16                      | 0.9                              | 70               | 204             | ---                         |
|                           |                                  | 46.67            | 212             | 3.92                        |
|                           |                                  | 35               | 223             | 9.31                        |
| 3Ø10+2Ø5                  | 0.61*                            | 130              | 142             | ---                         |
|                           |                                  | 86.7             | 149             | 4.56                        |
|                           |                                  | 65               | 146             | -1.40                       |

Note: * means experimental work.

2.5. Effects of stirrups on the flexural behavior of RC simply supported beams for different ratios of longitudinal reinforcement for \((M_u/V_u=1)\) and full scale

Five values selected of \(\rho_{\text{provided}}/\rho_{\text{max}}\) ratio. This effect studied with the change dimension of beam width, depth, and length which are 250 mm, 500 mm, and 5000 mm respectively as shown in figure 2 and for three value of spacing between stirrups for each case of ratio.
Table 7. Effect of $\frac{\rho_{\text{provided}}}{\rho_{\text{max}}}$ ratio on the ultimate load of beam.

| Longitudinal reinforcement | $\rho_{\text{provided}}/\rho_{\text{max}}$ ratio | Spacing between stirrups (mm) | Ultimate Load (KN) | Increment in ultimate load% |
|----------------------------|-----------------------------------------------|------------------------------|---------------------|-----------------------------|
| 2\16+1\10\10             | 0.3                                           | 230                          | 145                 | ---                         |
|                            |                                               | 153.3                        | 147                 | 1.38                        |
|                            |                                               | 115                          | 158                 | 8.97                        |
| 2\16+3\10\10             | 0.46                                          | 230                          | 190                 | ---                         |
|                            |                                               | 153.3                        | 196                 | 3.16                        |
|                            |                                               | 115                          | 198                 | 4.21                        |
| 3\20                       | 0.59                                          | 230                          | 234                 | ---                         |
|                            |                                               | 153.3                        | 241                 | 2.99                        |
|                            |                                               | 115                          | 245                 | 4.70                        |
| 3\20+2\10\10             | 0.68                                          | 230                          | 291                 | ---                         |
|                            |                                               | 153.3                        | 304                 | 4.47                        |
|                            |                                               | 115                          | 307                 | 5.50                        |
| 4\20+2\10\10             | 0.92                                          | 140                          | 302                 | ---                         |
|                            |                                               | 93.3                         | 318                 | 5.30                        |
|                            |                                               | 70                           | 329                 | 8.94                        |

Table 7 shows the effects of variation of $\frac{\rho_{\text{provided}}}{\rho_{\text{max}}}$ from 0.3 to 0.92 on the ultimate load with three values of spacing between stirrups. The results showed that when the ratio of $\frac{\rho_{\text{provided}}}{\rho_{\text{max}}}$ equal to 0.3 and spacing decrease from 230mm to 115mm the increment in ultimate load was equal to 8.97%. While the increments in ultimate load, due to duplicate stirrups were 4.21%, 4.7%, 5.5%, and 8.94% for ratio of $\frac{\rho_{\text{provided}}}{\rho_{\text{max}}}$ is equal to 0.46, 0.59, 0.68, and 0.92 respectively.

2.6. Effects of stirrups on the flexural behavior of RC fixed beams for different ratios of longitudinal reinforcement for ($M_u/V_u=1$) and full scale

Five values selected of $\frac{\rho_{\text{provided}}}{\rho_{\text{max}}}$ ratio. This effect studied with dimension 250, 500, and 5000 mm of beam width, depth, and length respectively.
Table 8. Effect of $\rho_{\text{provided}}/\rho_{\text{max}}$ ratio on the ultimate load of beam.

| Longitudinal reinforcement | $\rho_{\text{provided}}/\rho_{\text{max}}$ ratio | Spacing between stirrups (mm) | Ultimate Load (KN) | Increment in ultimate load% |
|----------------------------|-----------------------------------------------|-----------------------------|---------------------|-----------------------------|
| 2Ø16+1Ø10                  | 0.3                                           | 230                         | 350                 | ---                         |
|                            |                                               | 153.3                       | 352                 | 0.57                        |
|                            |                                               | 115                         | 355                 | 1.43                        |
| 2Ø18+3Ø10                  | 0.46                                          | 200                         | 410                 | ---                         |
|                            |                                               | 133.3                       | 415                 | 1.22                        |
|                            |                                               | 100                         | 417                 | 1.71                        |
| 3Ø20                       | 0.59                                          | 120                         | 433                 | ---                         |
|                            |                                               | 80                          | 449                 | 3.70                        |
|                            |                                               | 60                          | 451                 | 4.15                        |
| 3Ø20+2Ø10                  | 0.68                                          | 80                          | 450                 | ---                         |
|                            |                                               | 53.3                        | 461                 | 2.44                        |
|                            |                                               | 40                          | 467                 | 4.22                        |
| 4Ø20+2Ø10                  | 0.92                                          | 60                          | 470                 | ---                         |
|                            |                                               | 40                          | 485                 | 3.19                        |
|                            |                                               | 30                          | 506                 | 7.66                        |

Table 8 shows the effects of variation of $\rho_{\text{provided}}/\rho_{\text{max}}$ from 0.3 to 0.92 on the ultimate load with three values of spacing between stirrups. The results showed that when the ratio of $\rho_{\text{provided}}/\rho_{\text{max}}$ equal to 0.3 and spacing decrease from 230mm to 115mm the increment in ultimate load was equal to 1.43%. While the increments in ultimate load, due to duplicate stirrups were 1.71%, 4.15%, 4.22%, and 7.66% for ratio of $\rho_{\text{provided}}/\rho_{\text{max}}$ is equal to 0.46, 0.59, 0.68, and 0.92 respectively.

Table 9 shows the experimental and analytical results of beams with h/b is equal to 2 and with different ratios of $M_{\text{u}}/V_{\text{u}}$ and $\rho_{\text{u}}/\rho_{\text{max}}$. The results show that the increments in the ultimate load with increasing shear reinforcement for simply supported beams with small scale is larger than full scale beams and these increments are somewhat a little for beams with fixed ends.
3. Conclusions

1. The amount of confinement provided by lateral reinforcement are dependent not only upon the spacing of shear reinforcement but also on the distribution and ratio of flexural reinforcement.
2. Spacing of shear reinforcement is the most important parameter, because the qualities of concrete and steel are limited in practice. The effect of transverse reinforcement decreases drastically with increasing in the spacing.
3. Depending upon the arrangement of shear reinforcement and the relative areas of core and cover the presence of shear reinforcement appears to improve the overall ductility of the members.
4. The analytical investigations proved good agreement between the experimental and theoretical results for beams with variable spacing of stirrups, where the maximum difference between ultimate loads was 13%.
5. As a result of FEM analysis, it was found that the most increments in ultimate load with increasing shear reinforcement were found for ratios of $\rho_{\text{prov.}}/\rho_{\text{max}}$ larger than 80% for $h/b$ less than or equal to 2, where the increments were near to 9% when the stirrups increased by 100%, while for $h/b$ equal to 2.5 the optimal efficiency of stirrups on the ultimate load was at $\rho_{\text{prov.}}/\rho_{\text{max}}$ equal to 43% where the increments in the ultimate loads were 20.49% and 32.78% when the stirrups increased by 50% and 100% respectively.
6. The analytical results proved that for simply supported and fixed ends beams with full scale had increment in ultimate load equal to 8.94% and 7.66% respectively when $\rho_{\text{prov.}}/\rho_{\text{max}}$ was 0.92 and shear reinforcement increased by 100%.

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