Assessing provisions in Eurocode2 for anchoring reinforcing bars with bends

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Abstract. In Eurocode2, the design provisions allow for the anchorage length of reinforcing bars with bends to be calculated as the center line of the bar from the critical section of the member to the end of the straight portion of the bar beyond the bend, with no limit on the maximum value of the length beyond the bend (extension length). This paper thus presents statistical analysis for test results of reinforcing bars anchored with bends, collected from the literature, as a means to assess the performance of the provisions of Eurocode2. Strength of bent bars at an anchorage length depends on many parameters, including concrete compressive strength, embodied as a constant bond stress along the anchorage length; diameter of the bar; concrete side cover; spacing between bars, and confining reinforcement. Test results incorporated in this analysis include 113 simulated beam-column joint specimens with 16, 19, 22, 25, and 36 mm beam bars with stresses at anchorage failure ranging from 213 to 943 MPa, and concrete compressive strengths ranging from 18 to 114 MPa. Each specimen contained 2, 3, or 4 bent beam bars with clear spacing between them ranging from 2d_b to 11.4d_b. All specimens contained no confining reinforcement within the joint region and a constant concrete side cover of either 65 mm or 90 mm. The analysis showed that, for a given bar diameter, the predicted bar stress at anchorage failure with limitations as originally integrated on bond stress, concrete cover, and spacing between bars is reasonably safe. However, the ratio of test-to-calculated bar stress decreases as the ratio of extension to embedment length increases, resulting in an unconservative design when the extension length exceeds half of the embedment length. For rational designs, an upper limit on the extension length of half the embedment length is thus suggested.

Keywords: design provisions, anchorage, bent bars, extension length.

Introduction

In composite materials such as reinforced concrete, the internal stress developed between the concrete and the reinforcing bars has to be effectively transmitted to provide an adequate bond. In cases where the concrete dimensions are not sufficient to transmit these stresses in terms of straight bars, for example in external beam-column joints, bent bars are employed. Provisions in Eurocode2 [4] allow the calculation of the anchorage design length of a bent bar as the length of the centre line of the bar from the critical section of the member to the end of the straight portion of the bar beyond the bend, assuming a constant bond stress along the anchorage length. The behaviour of such bonds is, however, more complicated, primarily due to adhesion, friction, and mechanical interlock between the reinforcing bars and concrete [1]. These various mechanisms provide a nonlinear development of bond strength with increase of bar stress. Adhesion contribution is lost immediately with any slight slip between concrete and steel; as slip increases, the
friction between concrete and steel decreases, which leaves the mechanical interlock as the primary provider of bond. In addition to strength of bond, the anchorage strength of bent bars is a result of the bearing inside the bend, with compressive strength on the bar being up to seven times the compressive strength of concrete [5], resulting in concentration of stresses at the internal side of the bend. As a result, stress on the bar close to the end of the straight bars beyond the bend (extension length) converts to compression rather than tension as the extension becomes too long [12]. These findings contradict the basic assumption of the Eurocode2 provisions and raise questions about the adequacy of computing the anchorage length of bent bars with a constant bond stress and no limit on maximum value of extension length.

Much experimental work has been done to investigate the anchorage strength of bent bars in tension. The critical scenario is when beam reinforcement terminates in columns with bent bars. The data incorporated in such analysis is generally for simulated external beam-column joints. In 1975, Marques and Jirsa [9] tested 22 specimens without and with confining reinforcement; each specimen contained two bent bars, and the slip of the extension of the bent bars was found to be minimal compared to that of the bend and the bar ahead of it. Pinc et al. [10] evaluated 16 specimens with normal and lightweight concrete; at initial stresses, they noticed that most of the bond developed ahead of the bend. Soroushian et al. [13] tested seven specimens to investigate the pullout behaviours of bent bars, concluding that the anchorage strength increased with an increase of confining reinforcement. Hamad et al. [6] performed tests on 25 specimens with either black bent bars or coated bars; the anchorage strength was also found to increase as more confining reinforcement was provided and the anchorage strength of the bent coated bars was lower compared to that of the black bars. In 1995, Joh et al. [7] tested 19 specimens with more than two bent bars, then, in 1996, Joh and Shibata [8] completed their work by testing 13 specimens with different axial loads; the capacity of group of bent bars was found to increase with the increase of column axial load but only to an effective limit. Ramires and Russel [11] investigated the effect of high strength concrete by testing 21 specimens. Based on this limited number of specimens, Ramires and Russel [11] found that the contribution of concrete compressive strength to the anchorage of bent bars was appropriate with compressive strength to a power of 0.5. Sperry et al. [14,15,16,17] extended this by testing 337 specimens to investigate the effect of concrete compressive strength, bar diameter, confining reinforcement, angle of bend, and concrete side cover; with the database effectively extended, Sperry et al. [14,15,16,17] then concluded that the contribution of concrete compressive strength to the anchorage of bent bars was proportional to concrete strength to a power of 0.29. Finally, Ajaam et al. [2,3] tested 125 specimens to investigate the effect of more than two bent bars in different arrangements; the strength of bent bars decreased as the spacing between the bars decreased, with a similar reduction as the bars arranged close in horizontal or vertical directions.

Throughout this paper, a regression analysis approach based on the least squares method is used to characterize the trend lines of the data. The final solution, using the least squares method, minimizes the summation of the squares of residuals when formulating relations between the considered variables. For the purpose of this work, the least squares method was applied using Excel Worksheet.

Research Significant

Provisions in Eurocode2 [4] allow for the design anchorage length of bent bars to be calculated as the length of the center line of the bar from the critical section of the concrete member to the end of the extension length. The provisions applies no limit on the maximum value of the extension length and assumes constant bond stress along the bar. The complexity of bond mechanisms, effect of bearing stress inside the bend, and the contribution of long extension length contradict the provisions basic assumptions and simplifications. The aim of this paper is to collect data from literatures and perform a statistical analysis to assess the applicability of the provisions.
Provisions in Eurocode2

The design anchorage length for bent bars $l_{db}$ in tension is the minimum centerline length of the bar from the critical section of the member to the end of the straight portion of the bar beyond the bend, see Figure 1, and is calculated using Eq. (1)

$$l_{db} = \alpha_1 \alpha_2 \alpha_3 \alpha_4 \alpha_5 l_{b,req} \geq l_{b,min}$$  \hspace{1cm} (1)

where $\alpha_1$ is a reduction factor for the effect of the anchorage type with an assumption of the availability of a sufficient concrete; $\alpha_1$ is 0.7 when neither concrete side cover nor half of the clear spacing between bars is less than 3 times the bar diameter; otherwise $\alpha_1$ is 1.0. $\alpha_2$ is a reduction factor that controls the effect of minimum concrete side cover; $\alpha_2$ is calculated using the following equation:

$$\alpha_2 = 1 - 0.15(c_d - \phi)/\phi$$  \hspace{1cm} (2)

In Eq. (2), $c_d$ is the minimum of the concrete side cover or half of the clear spacing between bars. $\phi$ is the nominal bar diameter. $\alpha_3$ governs the effect of the transverse reinforcement. $\alpha_4$ controls the effect of transvers reinforcement when welded to the main reinforcement. $\alpha_5$ is a coefficient for the effect of confinement added by transverse pressure. For bent bars considered in this paper $\alpha_3$ through $\alpha_5$ have value of 1.0.

The required anchorage length $l_{b,req}$ considers the influence of the type of reinforcing steel and bond properties of the bent bars, and is calculated using the following equation:

$$l_{b,req} = (\phi/4) (\sigma_{sd}/f_{db})$$  \hspace{1cm} (3)

where $\sigma_{sd}$ is the design stress of the bent bars at the critical section and $f_{db}$ is the bond stress along the bar assumed to be constant. The value of $f_{db}$ is calculated using Eq. (4).

$$f_{db} = 2.25\eta_1 \eta_2 f_{ctd}$$  \hspace{1cm} (4)

$\eta_1$ governs the effect of quality of bond condition (equals to 1.0 for laboratory work). $\eta_2$ is 1.0 for bars with a diameter of less than 32 mm. the concrete tensile strength $f_{ctd}$ is calculated as a function of concrete compressive strength according to provisions 3.1.6 [4], not presented in here for limited space, with a limit on compressive strength of concrete to the value of C60/70.

For the purpose of this analysis, Eq. (1) through (4) is solved for the calculated bar stress at anchorage failure ($\sigma_{sd}$ is replaced by $f_{s,\text{Euro}}$):

$$f_{s,\text{Euro}} = (4l_{bd} f_{db})/(\alpha_1 \alpha_2 \phi)$$  \hspace{1cm} (5)
Where $l_{bd}$ is the measured anchorage length from tests and $f_{db}$ is calculated using values of the mean compressive strength of concrete cylinders at the test day.

**Data and Analysis**

Results of tests used in the analysis are carefully selected from literatures to serve the purpose of this paper. Strength of bent bars embedded in concrete is the summation of the strength of concrete itself and the strength added by confining reinforcement with approximately 80% of the strength coming from the concrete [2,14]. So, it would be wise, when evaluate provisions of anchoring reinforcement, to consider specimens with no confining reinforcement within the joint region. One hundred thirteen simulated beam-column joints from the literature are incorporated in this analysis. A simulated beam-column joint is a joint with only the column cast, where the beam is represented by the bent bars and a compression block. In all selected data, tensile load was applied monotonically to the bent bars using hydraulic jacks. The loading was paused in several intervals to chase the cracks until about the failure then loaded continuously to anchorage failure.

The specimens contained 16, 19, 22, 25, or 36 mm beam bars (specimens with 19 and 22 mm are limited) with stress at anchorage failure ranging from 213 to 943 MPa. Concrete compressive strength ranged from 18 to 114 MPa. Each specimen contained 2, 3, or 4 bent beam bars with clear spacing between bars that range from $2d_b$ to $11.4d_b$. All specimens contained no confining reinforcement within the joint region and a constant concrete side cover of either 65 mm or 90 mm. The bent bar where embedded to the end of the columns with a nominal concrete back cover of 50 mm. The embedment length, or the equivalent anchorage length, is the distance from the critical section to the back of the extension. Specimens had embedment length ranging from 125 to 660 mm.

The analysis is carried out in two parts, subsets of specimens with same bar size (16, 25, and 36 mm) are compared with provisions in Eurocode2 [4] to examine the effect of concrete compressive strength, concrete side cover, spacing between bars, and bar stress at anchorage failure. Then, the effect of the ratio of extension length to embedment length is investigated utilizing all available data.

**Specimens with 16-mm bent bars**

Figure 2 shows the ratios of test to calculated bar stress $f_{su}/f_{s,\text{Euro}}$ at anchorage failure of the subset of 26 beam-column joint specimens containing 16-mm bent bars plotted with compressive strength of concrete. The value of test stress $f_{su}$ at anchorage failure is the maximum average anchorage force of bent bars in the specimen divided by the nominal bar area. The value of the calculated stress $f_{s,\text{Euro}}$ is based on Eq. (5). The 26 beam-column joint specimens, 18 specimens contained two bent bars with clear spacing between the bars ranging from 160 to 180 mm, corresponding to 10 to 11.3 times the bar diameter. Specimens with two bent bars are denoted with solid triangles in Figure 2. The other 8 specimens contained (4) specimens with three bent bars and the other four with four bent bars with clear spacing between the bars ranging from 45 to 80 mm, corresponding to 2.8 to 5 times the bar diameter. These specimens are denoted with open diamonds. Compressive strength of concrete of the specimens ranged from 33 to 109 MPa and the nominal side cover was 65 or 90 mm.
Figure 2: Ratios of test to calculated bar stress $f_{su,Euro}$ versus compressive strength of concrete for specimens with 16-mm bent bars

The solid line, in Figure 2, is the trend of the specimens with two bent bars. This trend line is approximately horizontal indicating that, with the embodied cap on compressive strength of concrete, the effect of compressive strength is well represented by the provisions. However, the dashed trend line is the actual behavior, when separating the data at 60 MPa (the cap on the compressive strength), the trend line has a negative slope as the compressive strength increase up to 60 MPa then positive slope beyond 60 MPa. As a result of this behavior, the critical case, minimum value of $f_{su,Euro}$, is at a compressive strength of about 60 MPa. For specimens with two bent bars, the values of $f_{su,Euro}$ ranged from 0.6 to 1.21 with a mean value of 0.86. Of the whole group, the 26 specimens, 16 specimens had values of $f_{su,Euro}$ below 1.0, that is 62%. It is important to note that majority of the specimens with ratios of $f_{su,Euro}$ below 1.0 has large values of the ratio of extension length to embedment length, $l_e/l_{eh}$ (this will be investigated in details later).

Specimens with more than two bent bars has $f_{su,Euro}$ ranging from 0.74 to 1.63 with a mean value of 1.13 (higher than that of specimens with two bent bars). The product of reduction factors for available cover and side cover are less for specimens with two bent bars than that for specimens with more than two bent bars, as clear spacing between bars decreased. This may results in over estimation of anchorage strength of small bent bars.

Specimens with 25-mm bent bars
Figure 3 shows the ratios of test to calculated bar stress $f_{su,Euro}$ at anchorage failure of a subset of 46 beam-column joint specimens containing 25-mm bent bars plotted with compressive strength of concrete. Thirty five specimens contained two bent bars with clear spacing between the bars ranging from 220 to 265 mm, corresponding to 8.6 to 10.4 times the bar diameter. Specimens with two bent bars are denoted with solid squares. The other 11 specimens contained three bent bars with clear spacing between the bars ranging from 50 to 115 mm, corresponding to 2.0 to 4.5 times the bar diameter. These specimens are denoted with open squares. The compressive strength of the specimens ranged from 31 to 114 MPa and the nominal side cover was 65 or 90 mm.
Figure 3: Ratios of test to calculated bar stress $f_{u/Euro}$ versus compressive strength of concrete for specimens with 25-mm bent bars

The trend of the specimens with two bent bars, the solid line, has a slight positive slope resulting in a safer prediction as the compressive strength increases; however, similar to specimens with 16-mm bent bars in (Figure 2), data points with minimum values of $f_{u/Euro}$ in (Figure 3) are still located at compressive strength of about 60 MPa. Specimens with two bent bars had values of $f_{u/Euro}$ ranged from 0.53 to 1.73 with a mean value of 1.14. The plot show a high range of scatter, even though, when compared to specimens with 16-mm bent bars, the provisions predict safer values of stresses as the bar diameter increased. The concrete side cover with values ranging from 65 to 90 mm used in the specimens simulates what would be found in practical application. Therefore, the values of the reduction factors for concrete availability and concrete side cover will be at the highest for bar diameters of 25 and larger. For the 46 specimens with two bent bars, 16 specimens had values of $f_{u/Euro}$ below 1.0, that is 35% similar to specimens with 16-mm bent bars, most of specimens with ratios of $f_{u/Euro}$ below 1.0 has large values of the ratio of extension length to embedment length.

Specimens with three bent bars has $f_{u/Euro}$ ranging from 0.64 to 1.17 with a mean value of 0.93. When comparing the mean value, specimens with three bent bars has a value of lower than that of specimens with two bent bars but the distribution of the data, in Figure 3, is within the overall scatter.

Specimens with 36-mm bent bars

Figure 4 shows the ratios of test to calculated bar stress $f_{u/Euro}$ at anchorage failure of a subset of 23 beam-column joint specimens containing 36-mm bent bars plotted with compressive strength of concrete. Twenty specimens contained two bent bars with clear spacing between the bars ranging from 180 to 350 mm, corresponding to 5 to 9.7 times the bar diameter. Specimens with two bent bars are denoted with solid triangles. The other 3 specimens contained three bent bars with clear 100 mm, corresponding to 2.7 times the bar diameter. These specimens are denoted with open triangles. The compressive strength of the specimens ranged from 34 to 112 MPa and the nominal side cover was 65 or 90 mm.
Figure 4: Ratios of test to calculated bar stress $\frac{f_{su}}{f_{s;Euro}}$ versus compressive strength of concrete for specimens with 25-mm bent bars

Comparing to trend lines of smaller bars (Figures 2 and 3), the trend of the specimens with two bent bars (Figure 4), the solid line, has a higher positive slope indicating a more conservative result as the compressive strength increases. Here the effect of the cap on compressive strength of concrete is not clear as limited data available for low compressive strength. Specimens with two bent bars had values of $\frac{f_{su}}{f_{s;Euro}}$ ranging from 0.8 to 1.65 with a mean value of 1.10. As for specimens with 16 or 25-mm bent bars, specimens with ratios of $\frac{f_{su}}{f_{s;Euro}}$ below 1.0 has large values of the ratio of extension length to embedment length. Specimens with more than two bent bars has $\frac{f_{su}}{f_{s;Euro}}$ ranging from 0.90 to 1.09 with a mean value of 1.0 (lower than that of specimens with two bent bars but within the overall range).

Effect of ratio of extension to embedment lengths

Analysis of the subsets containing 16, 25, and 36-mm bent bars indicated that most of the specimens with ratios of $\frac{f_{su}}{f_{s;Euro}}$ below 1.0 has large values of ratio of extension to embedment lengths $l_e/l_{ch}$. Figure 5 presents the ratios of test to calculated bar stress $\frac{f_{su}}{f_{s;Euro}}$ at anchorage failure of all data available, 113 specimens, plotted with the ratios of extension to embedment lengths, $l_e/l_{ch}$. The Embedment length is the measured length from the critical section, in this case the front face of the columns, to the back of the extension. Embedment length ranged from 125 to 660 mm, corresponding to values of $l_e/l_{ch}$ of 0.14 to 0.56. The trend line has a negative slope indicating that, as expected, the ratio of $\frac{f_{su}}{f_{s;Euro}}$ decrease as the ratio of $l_e/l_{ch}$ increases. Specimens has $\frac{f_{su}}{f_{s;Euro}}$ ranging from 0.53 to 1.73 with a mean of 1.07. From the 113 specimens, 45 from them specimens has $\frac{f_{su}}{f_{s;Euro}}$ below 1.0, corresponding to 40%.

![Figure 4](image-url)
To overcome this problem, when solving the equation of the trend line, presented in Figure 5, the value of the ratio $l_e/l_{eh}$ at which $f_{su}/f_{s,\text{Euro}}$ becomes below 1.0 is 0.5. This value can be used as an upper limit on the ratio of extension to embedment lengths $l_e/l_{eh}$. Figure 6 present the ratios of test to calculated bar stress $f_{su}/f_{s,\text{Euro}}$ at anchorage failure for same data in Figure 5 plotted with the ratios of extension to embedment lengths but with anchorage length used to calculate $f_{s,\text{Euro}}$ is limited to half of embedment length (0.5 $l_{eh}$). The trend line in Figure 6 has a slight positive slope indicating that the effect of large values of $l_e/l_{eh}$ was successfully collaborated using the upper limit; specimens has $f_{su}/f_{s,\text{Euro}}$ ranging from 0.81 to 2.09 with a mean of 1.37. Only 10 specimens has values of $f_{su}/f_{s,\text{Euro}}$ below 1.0, corresponding to 8%.

**Figure 5:** Ratios of test to calculated bar stress $f_{su}/f_{s,\text{Euro}}$ versus ratios of extension to embedment lengths $l_e/l_{eh}$, with no limit on $l_e$.

\[ y = -0.9871x + 1.5073 \]
Summary and Conclusions
Results of 113 simulated beam-column joint specimens, collected from the literatures, are analyzed to evaluate the performance of the provisions adopted in Eurocode2 [4] for anchoring reinforcing bars with bends. The variables investigated are compressive strength of concrete, bar diameter, number bars, clear spacing between bars, concrete side cover, and ratio of extension to embedment length. Specimens contained 2, 3, or 4 bent embedded to the back of the columns with a nominal back concrete cover of 50 mm. The bent bars were 16, 19, 22, 15, or 36 mm with embedment length ranging from 125 to 660 mm, corresponding to ratio of extension to embedment length ranging from 0.14 to 0.56. The analysis results in the following conclusions:
1- With the cap on compressive strength of concrete, the effect of concrete strength on anchorage strength of bent bars is well represented.
2- Use of reduction factors with small bars may result in over estimation of anchorage strength.
3- As the ratio of extension length to embedment length increases the ratio of test to calculate bars stress decreases, resulting in an unconservative design when the extension length exceeds half of the embedment length.
4- Use of an upper limit of the extension length half of the embedment length was successful in collaborate the effect of large ratios of extension to embedment length.

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