STUDIES TO MINIMIZE THE EFFECTS OF BOND SLIPPAGE IN EXTERIOR JOINTS OF R/C DUCTILE MOMENT RESISTING FRAMES

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SUMMARY

A mathematical model of a deformed bar anchored in a concrete block described in Ref. 1 has been extended to cover also hooked bars. The analytically predicted response of straight and hooked bars anchored at exterior joints compares well with available experimental results. An extensive numerical investigation has been carried out to show the influence of significant parameters on the anchored bar behavior. The results of this investigation are used to offer practical recommendations for the anchorage of bars at exterior joints.

INTRODUCTION

It is well known that one of the main sources of stiffness degradation of R/C moment resistant space frames that occurs with the increase in severity of the hysteretic requirements is the increase in bond slippage of the beam bars along their anchorage lengths in the joints. In order to be able to predict the bond slippage behavior of bars anchored at exterior joints, the analytical model of a deformed bar embedded in a well confined concrete block and subjected to generalized excitations described in Ref. 1 is extended to cover also bars terminating in a standard 90-degree hook. The extension is based on the elaboration of test results given in Ref. 2. The analytically predicted response of straight and hooked bars anchored at exterior joints is compared with available results of tests under monotonic and cyclic loadings (Ref. 4). Finally the model is used to investigate the influence of various parameters on the hysteretic response of anchored deformed bars.

MATHEMATICAL MODEL OF ANCHORED BARS

Only a very brief description is given here. Details can be found in Refs. 1 and 2.

The behavior of a bar of finite length embedded in a concrete block is idealized as a one-dimensional problem and modeled using the ordinary nonlinear differential equation $dN(x)/dx + q(x) = 0$, where $q(x) = \pi \cdot d_b \cdot \tau(x)$ and $N(x) = A_s \cdot \sigma(x)$, with d_b diameter of the bar and A_s area of the cross section. The equation connects the axial force in the bar, N, to the resultant per unit length of the bond stresses on the perimeter of the bar, q. It has to be coupled with the constitutive laws for steel and bond, $\sigma = \hat{\sigma}(\varepsilon(x))$ and $\tau = \hat{\tau}(s(x))$, where $s(x)$ is the slip along the bar and $\varepsilon(x)$ the steel strain

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which is set equal to ds/dx, thus neglecting, for simplicity, the deformation of concrete. Boundary values are specified at the two end points of the bar. Together with the differential equation they define a non-linear two boundary value problem, which is solved here numerically by using a "shooting technique".

The used local bond stress-slip relationship $\tau = \hat{\tau}(s(x))$ is illustrated in Fig. 1. It takes into account all significant parameters that appear to control the behavior observed in experiments and consists of a monotonic envelope, unloading -, friction -, reloading - branch and reduced envelope. Details about the different branches of the bond model are given in Ref. 3. The model is valid only for well confined concrete regions. However, by applying certain modifications as discussed in Refs. 1 and 3, it can also be used to describe the bond behavior at the outer unconfined regions of a joint.

Fig. 2 shows typical steel stress-slip relationships for 90-degree hooks embedded in well confined concrete under monotonic and cyclic loading. The analytical model of the local bond stress-slip relationship (Fig. 1) can easily be extended to describe this observed behavior. The hook is idealized as a straight bar with a length equal to the value l'_d between the beginning of the bend and the tangent to the hook (see Fig. 2). By assigning proper values to the parameters describing the model (Ref. 2), the experimentally observed behavior can be reproduced with sufficient accuracy (Fig. 2).

A bilinear model was used for the stress-strain relationship of the bar.

COMPARISON OF ANALYTICAL PREDICTIONS OF THE RESPONSE OF BEAM BARS ANCHORED AT EXTERIOR JOINTS WITH TEST RESULTS

The numerical model of an anchored straight and hooked bar was used to compare the predicted response with experimental results obtained in tests carried out by Hawkins et.al. and summarized in Ref. 4. The used stub cantilever specimens represented exterior beam column connections. The specimens were proportioned and reinforced so that the influence of shear deformations and diagonal cracking were minimized. The relation between cover and bar diameter was 1.9 for bars with $d \sim 32$ mm and 4.0 for 19 mm bars and 25 mm bars. The cover behind the standard 90-degree hook as defined in Ref. 5 was 50 mm. The vertical column bars were enclosed by relatively widely spaced stirrups.

The comparison was done for 19 specimens with Grade 60 deformed bars (f_y = 415 N/mm² to 470 N/mm²). Main variables in these tests were the bar diameter ($d_b \sim 19$ mm to 32 mm), the anchorage length (l_d/d_b = 16 to 24), the concrete strength ($f_c' \sim 20$ N/mm² to 35 N/mm²), the type of anchorage (straight bars or bars terminating in a 90-degree hook) and the loading history. The characteristic values for the local bond stress-slip relationships along the embedment length were taken from Ref. 3 for the specific concrete strength and bar diameter. In the cantilever tests the beam bars were placed about 800 mm above the bottom of the formwork which might have resulted in a lower bond strength (top bar effect). Therefore the characteristic bond strength values given in Ref. 3 were reduced according to Ref. 5 by 30 %. The characteristic values defining the model of the 90-degree hook were chosen in accordance with Ref. 2.

As example of the extensive calculations, in Figs. 3 to 6 a comparison between the numerically obtained force-slip relationships for the loaded bar

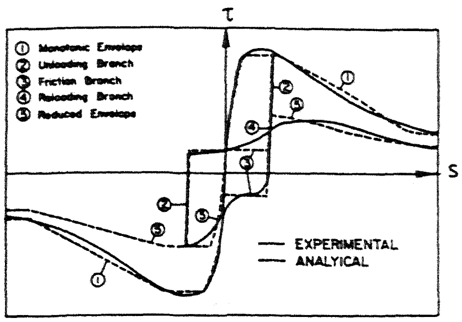


Fig. 1 Analytical model for local bond stress-slip relationship

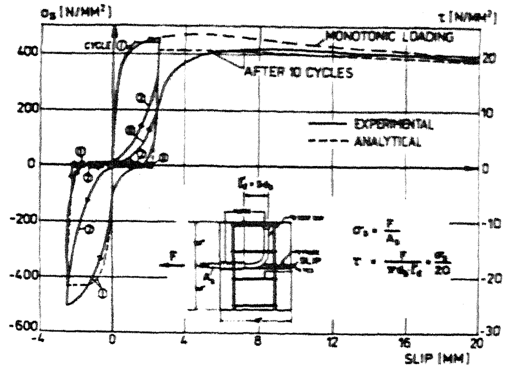


Fig. 2 Comparison of experimental and analytical results on steel stress-slip relationship of hooks

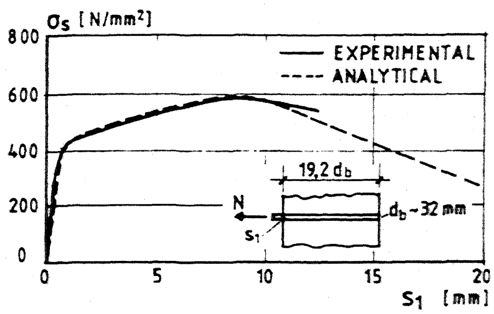


Fig. 3 Comparison of experimental and analytical results, test 101 of Ref. 4

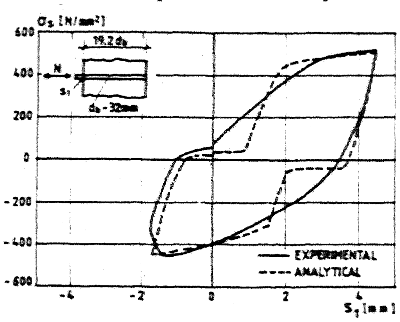


Fig. 4 Comparison of experimental and analytical results, test 106, cycle 10 of Ref. 4

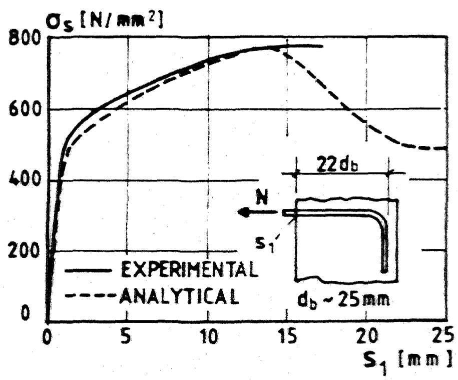


Fig. 5 Comparison of experimental and analytical results, test B 81 of Ref. 4

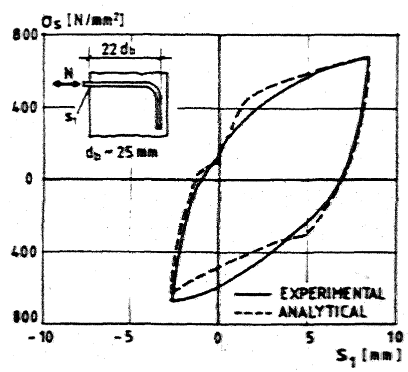


Fig. 6 Comparison of experimental and analytical results, test B 85, cycle 4 of Ref. 4

end with corresponding experimental results are shown. As can be seen, the obtained accuracy of reproduction of experimental results seems sufficient for practical purposes. In general the model was successful in reproducing most of the experimental results for the various bond conditions but with the following exception.

If in the tests with bars terminating in a 90-degree hook yielding of the steel had almost penetrated to the beginning of the bent, the concrete cover behind the hook was pushed off in the next compression cycle. This behavior was mainly observed in tests with 32 mm bars and a relatively short lead-in length (15.75 d_b) after severe cycling. It resulted in an almost complete loss or significant reduction of the strength of the hook in the following compression or tension loadings respectively and a corresponding strength degradation of the anchored bar. Because the assumed analytical model of the hook (Fig. 2) is valid only for well confined concrete, it does not reflect the strength degradation associated with spalling of the cover behind the hook. Therefore in these cycles the analytically predicted strength of the anchored bar was much higher than observed in the experiments. In Ref. 4 it is proposed to assigne the local bond stress-slip relationships of a straight bar (Fig. 1) also in the region of the hook. However, in this case the analytically predicted strength was too low as compared with the experimental results.

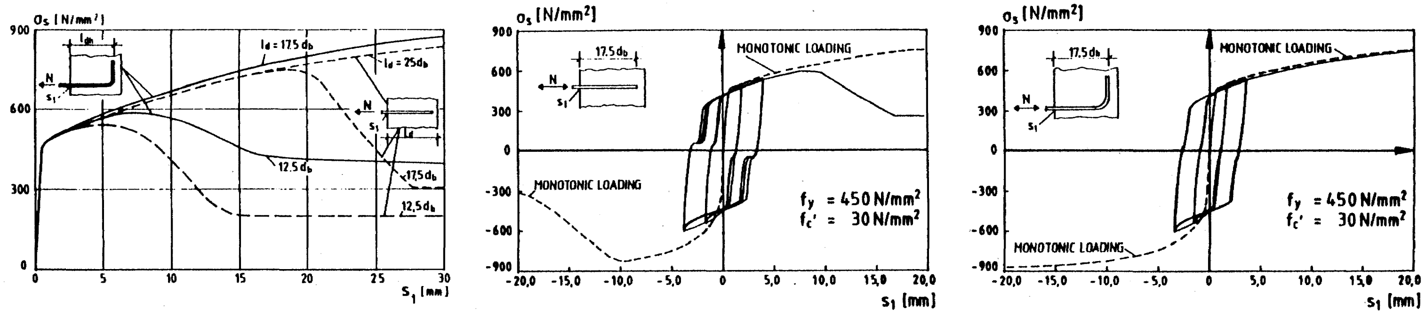
ANALYTICAL STUDIES

The influence of some important parameters on the behavior of deformed beam bars (d_b = 25 mm) anchored at exterior well confined joints was investigated by determining the model response to imposed histories of displacement (slip), just as it would be done in an experiment. The studies were done for monotonic loading in tension and cyclic loading. In the latter case the loading history consisted of 3 fully reversed cycles between constant slip values which were chosen to give steel strains ε_s = 15 mm/m under monotonic tension loading, followed by 3 reversed cycles between constant slip values corresponding to steel strain ε_s = 30 mm/m. The assumed bond behavior along the embedment length was chosen - as in the previous comparison with test results - in accordance with the proposals given in Refs. 2 and 3. In the calculations steel strength and ultimate steel strain were not limited so that all bars could reach the stress at peak anchorage resistance.

Type of Anchorage

In this series of numerical tests, the concrete strength (f_c' = 30 N/mm²), the steel characteristics (yield stress f_y = 450 N/mm² and strain hardening ratio E_1/E_o = 0.017) and the anchorage length (l_d = 12.5 d_b and 17.5 d_b respectively) were held constant. Varied was the type of anchorage (straight or hooked). The lead-in length of bars terminating in a standard 90-degree hook as defined in Ref. 5 was chosen so that the total anchorage length l_{dh} measured between critical section to outside end of hook (see Fig. 7a) was the same as for straight bars ($l_d = l_{dh}$). The model response was calculated for bottom beam bars.

In Fig. 7 the steel stress-slip relationships for the loaded end of bars with an anchorage length $l_d = l_{dh}$ = 17.5 d_b are plotted. Under monotonic loading (Fig. 7a), the response is not much influenced by the type of anchorage up



a) b) c)

Fig. 7 Influence of type of anchorage on the response of anchored beam bars, $l_d = l_{dh} = 17.5\ d_b$

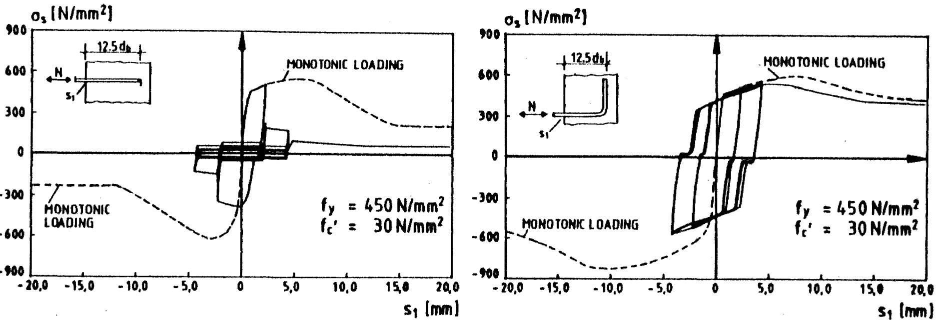


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Fig. 8 Influence of type of anchorage on the response of anchored beam bars, $l_d = l_{dh} = 12.5\ d_b$

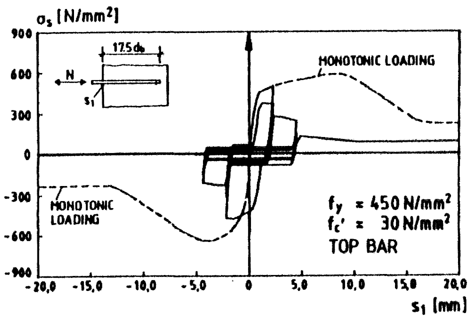


Fig. 10 Response of anchored top bars

to a slip of about 17 mm. The corresponding steel stress and steel strain are $\sigma_s \sim 700$ N/mm² and $\varepsilon_s \sim 70$ mm/m respectively. Only if larger slip values are induced, straight and hooked bars behave differently. However, steel strains $\varepsilon_s > 70$ mm/m are not likely to occur even during severe earthquakes. Cyclic loading caused a slight pinching of the hysteretic loops of anchored straight bars and a decrease of the maximum resistance compared to monotonic loading (Fig. 7b). On the contrary to that cyclic loading had very little effect on the behavior of anchored hooked bars (Fig. 7c).

The influence of the type of anchorage on the bar behavior during cyclic loading was more pronounced for an anchorage length $l_d = l_{dh} = 12.5\ d_b$ (Fig. 8). This is due to the fact that in well confined concrete a standard 90-degree hook can anchor almost the force at yield and cycling does not must influence the envelope of the force-slip relationship of the hook (Fig. 2).

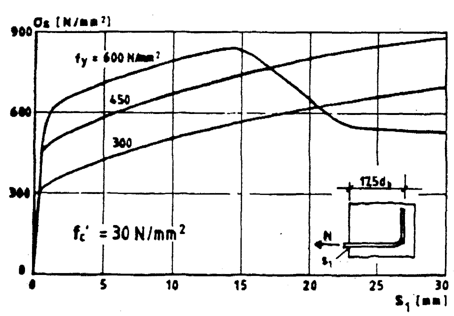
Anchorage Length

Figs. 7 and 8 can also be used to study the influence of the anchorage length on the bar response. Under monotonic loading the strength of the anchorage was almost proportional to the anchorage length (Fig. 7a). The hysteretic loops of straight anchorages with $l_d = 12.5\ d_b$ were severely pinched (Fig. 8a), due to an almost complete damage of bond along the entire embedment length. An increase of the anchorage length to $l_d = 17.5\ d_b$ resulted in a significant improvement of the hysteretic behavior (Fig. 7b). The effect of cyclic loading on the behavior of hooked bars with $l_{dh} = 12.5\ d_b$ was almost the same as on the behavior of straight bars with $l_d = 17.5\ d_b$ (compare Fig. 8b with Fig. 7b).

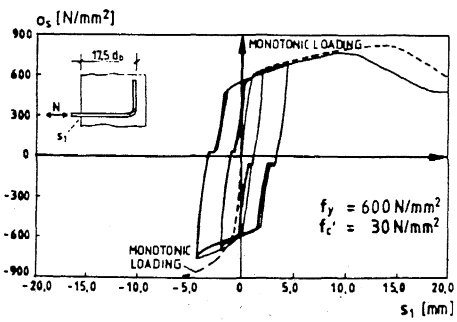
Yield Stress

In this set of numerical tests the response of a bottom beam bar terminating in a standard 90-degree hook ($l_{dh} = 17.5\ d_b$, $f_c' = 30$ N/mm²) was calculated. The yield stress was varied between 300 N/mm² and 600 N/mm². The main results are plotted in Fig. 9.

Under monotonic loading for slip values $s_1 < 15$ mm the anchorage resistance was almost proportional to the yield stress (Fig. 9a). However, the strength



a)



b)

Fig. 9 Influence of yield stress on the response of anchored beam bars of the anchorage was almost independent of the yield stress, but the slip at which the maximum resistance was reached increased considerably with decreasing yield stress. The deterioration of the resistance of anchorages caused by cyclic loading well into the plastic region increased with increasing yield stress (compare Fig. 9b with Fig. 7c). The influence of the yield stress was more pronounced for shorter anchorages. These findings are in agreement with earlier studies for interior joints (Ref. 1).

Position Of Bar During Casting

In the preceding studies a bond behavior as valid for bottom bars was assumed. The bond behavior of top beam bars might be influenced by the depth of concrete beneath the bar during casting. To study this influence, the response of a straight bar (l_d = 17.5 d_b) subject to cyclic loading was calculated, assuming a reduction of 30 % of the characteristic bond strength values. This reduction is proposed in Ref. 5. By comparing the resulting steel-stress slip relationship (Fig. 10) with Fig. 7b it can be seen that cyclic loading caused significant more bond deterioration for top bars than for bottom bars. The top bar effect might be reduced by using low-slump and well compacted concrete.

CONCLUSIONS AND RECOMMENDATIONS

From the results obtained in this study the following main observations can be made:

(1) The proposed mathematical model allows to predict with accuracy sufficient for practical purposes the response of straight and hooked deformed reinforcing bars anchored at exterior well confined joints of ductile moment resisting R/C frames under generalized excitations.

(2) For given hysteretic requirements the performance of anchorages at exterior joints improves with increasing anchorage length and with decreasing yield stress. This is in accordance with the results of a study for interior joints (Ref. 1).

(3) The performance of bars terminating in a standard 90-degree hook and anchored in well confined concrete under monotonic and cyclic loading is superior to that of straight bars with the same anchorage length (l_d=l_{dh}). To ensure this behavior, the confinement should satisfy at least the requirements given in Ref. 5, Sections 12.5.3.2 and 12.5.5.

(4) The necessary anchorage length is significantly influenced by hysteretic requirements and required performance of the anchorage during cycling (Ref. 1). If hysteretic requirement as given in the previous chapter are assumed and almost stable hysteretic loops are required, an anchorage length $l_d \sim 20\ d_b$ or $l_{dh} \sim 15\ d_b$ is necessary for straight bars or bars terminating in a standard 90-degree hook respectively. These values are valid for deformed Grade 60 ($f_y \sim$ 415 N/mm²) bottom beam bars anchored at well confined exterior joints with a specified concrete strength f_c' = 30 N/mm². They take into account that the actual yield stress may be higher than the specified value. For top bars a 40 % larger anchorage length is recommended. If the concrete is not well confined, larger anchorage lengths are necessary. Furthermore hooks might negatively influence the anchored bar behavior under cyclic loading (Ref. 4).

(5) If the width of columns at exterior joints is too small to accomodate the required anchorage lengths, the formation of plastic hinges in girders near column faces should be avoided by proper detailing to avoid excessive slip and damage of bond. This is in accordance with earlier recommendations (Ref. 6).

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