HYSTERETIC BEHAVIOR OF REINFORCING DEFORMED HOOKED BARS IN R/C JOINTS

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SUMMARY

The force-slip relationships of deformed hooked bars embedded in well confined concrete and subjected to monotonic and cyclic loadings were experimentally studied. The results were used to deduce an analytical model for the hook behavior under generalized excitations. The model is similar to the one for the local bond stress-slip relationship of deformed bars /3,4/, but with some modifications to account for the different behavior of hooks. The main results of this study are reported.

1 INTRODUCTION

Experimental and analytical studies have shown that the inelastic response of R/C frame structures, which have been designed according to present seismic-resistant design practice, to severe ground motions is very sensitive to the behavior of the frame joints. The hysteretic behavior of these joints shows that as the severity of the demanded hysteretic behavior of the beam main reinforcing bars increase there is a considerable increase in slippage of these bars along their embedment length along the joint /1/.

Hooks are commonly used to anchor main beam bars in exterior beam-column joints of R/C moment resisting frames. The hysteretic behavior of such joints under severe seismic excitations is highly dependent on the hysteretic behavior of the hooks. Because the latter is not known yet, tests were carried out to obtain force slip relationships for hooked bars which were used to deduce an analytical model describing the behavior of hooks under monotonic and random cyclic loading. In this paper the main results of these investigations are reported. Details are given in /2/.

2 EXPERIMENTAL PROGRAMM

The test specimens (Fig. 1) represented a part of an exterior beam-column joint. Only the hook was anchored in concrete ($f_c' \sim 30$ N/mm²). The hook was bent around a mandrel having a diameter of 6 d_b, the bar length before and beyond the bent was 1 d_b and 5 d_b respectively. # 8 deformed bars ($d_b = 25$ mm) were used in the experiments. The secondary reinforcement consisted of # 4 (12,7mm) bars.

The test specimen was installed in a specially designed testing frame (Fig. 2) and was loaded by a hydraulic servo controlled universal testing maschine having a capacity of 1350 kN, which allowed the application of prescribed tension or compression forces, or displacements, to the embedded hook. The tests were run under displacement control by subjecting the threaded loading end of the bar to the required force needed to induce the

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[II] Professor, University of California, Berkeley, USA desired slip, which was measured at the beginning of the hook, using a linear variable differential transformer (Fig. 2) and was controlled as in the comparable study with straight bars at a rate of 1.7 mm/min. To measure the slip a # 2 (6.4 mm) probe was welded to the bar, which was not bonded to the concrete and reached to the outside of the specimen. The slip at the unloaded bar end was measured as well. Load and slip at the loaded and unloaded bar end were recorded by two X-Y recorders.

The influence of the following parameters were investigated: 1) monotonic loading in tension and compression, 2) cyclic loading between given slip values with value of peak slip (s_{max} = 1 mm to 15 mm) and number of cycles (1 to 10) as main parameters, and 3) position of hook in relation to direction of casting (hook bent in and against casting direction). Altogether 24 specimens were tested.

3 EXPERIMENTAL RESULTS

The hooks were able to anchor almost the force at yield ($f_y \sim 500$ N/mm²) of the bar in tension as well as in compression loading. Well below the maximum resistance splitting cracks developed at the sides of the specimens, which at maximum load ran along almost the entire hook (Fig. 3). Their growth was controlled by the secondary reinforcement (see Fig. 1). With increasing slip the concrete cover perpendicular to the plane of the hook spalled off. Usually the tests were stopped at a slip of 20 mm at the beginning of a hook. The slip at the unloaded bar end was then approximately 12 - 15 mm and the load carried by the hook was still about 90 % of the masimum value. With increasing slip the hook was pulled (tension loading) or pushed (compression loading) respectively into the concrete, leaving there a big indentation (Fig. 4). The concrete between the protuding lugs of the ribs along the hook was completely sheared off. That means, that at large slip values the anchored force was mainly transfered to the concrete by friction, which was favourably influenced by the pressure put on the concrete by the hook, and the bending resistance of the hook against pullout. The latter effect was clearly indicated by the observed cracks along the end part of the hook (Fig. 3).

Typical steel stress-slip relationships for hooks under monotonic and cyclic loadings are plotted in Fig. 5. The slip was measured at the beginning of the hook. The corresponding bond stresses are given as well. They were calculated by assuming a constant bond stress along the equivalent length l_d', measured between the beginning of the embedment and the tangent at the hook (see Fig. 5). This length was $l_d' = 5\ d_b$. The embedment length measured along the hook was about 10.7 d_b. For comparison bond stress-slip relationships for straight bars with an embedment length of 5 d_b, obtained under comparable testing conditions, are shown in Fig. 6. The test results can be summarized as follows:

(a) The behavior of hooks loaded in compression was slightly superior to that of hooks loaded in tension.

(b) The maximum resistance of a hook under monotonic loading was about 60 to 70 percent larger than those of a straight bar with an anchorage length corresponding to the equivalent length l_d' (compare Fig. 5 with Fig. 6). This is due to the larger bonded length of the hook, which was more than 2 l_d'.

(c) Under monotonic loading the resistance of hooks was almost constant over a very large range of slip (Fig. 5). On the contrary, the bond resistance of straight bars dropped down to about 1/3 of the maximum value at large slip values (Fig. 6).

(d) Cycling loading produced a significant deterioration of stiffness and strength of the anchored hook at slip values smaller than the peak slip values, between which the hook was cyclically loaded, with increasing number of cycles (Fig. 5). At peak slip the resistance deteriorated at almost the same rate as the bond resistance of straight bars (compare Fig. 6). However, the force-slip relationship at larger slip values than the peak slip during previous cycles followed almost the curve for monotonic loading. This behavior was independent of the value of the peak slip. On the contrary straight bars, cycled between rather large slip values, did not reach the monotonic envelope again (Fig. 6).

(e) The frictional bond resistance of hooks during cyclic loading was significantly smaller than for straight bars.

(f) Hooks bent in setting direction of the concrete reached the maximum resistance at larger slip values than hooks bent against the direction of casting. Otherwise the influence of the position of the hook during casting on the load-slip behavior under monotonic and cyclic loading was negliable.

The different bond behavior of hooks compared to straight bars can be explained as follows:

The maximum bond resistance of straight bars is controlled by the initiation of a shear failure in a part of the concrete between lugs. With increasing slip an increasing area of concrete between lugs is effected by this shear failure, thus reducing the bond resistance. When the concrete corbels are completely sheared off, only frictional resistance between rough concrete surfaces is left. Cyclic loading with full reversals of slip damages the concrete between lugs from both sides of the corbel and grounds off the concrete at the cylindrical surface where shear failure occured, thus causing a reduction of the bond resistance compared to monotonic loading.

The maximum bond resistance of hooks is probably also controlled by the initiation of a shear failure in a part of the concrete between lugs. However, with increasing slip an increasing part of the total force is transfered to the concrete by high friction and by the resistance of the bent bar against pullout, keeping the anchored force almost constant over a large slip range. Note, that this behavior is only possible when destruction of concrete is resisted by heavy secondary reinforcement.

4 ANALYTICAL MODEL FOR THE FORCE-SLIP RELATIONSHIP OF HOOKS

In /3,4/ an analytical model for the local bond stress-slip relationship of deformed bars under generalized excitations is presented (Fig. 7). It consists of an envelope for monotonic loading, and of an unloading-, frictional- and reloading branch as well as a reduced envelope for cyclic loading. The monotonic envelope starts with an initial non linear relationship $\tau = \tau_1 (s/s_1)^{\alpha}$ valid for $s \leq s_1$, followed by a plateau with $\tau = \tau_1$ for $s_1 \leq s \leq s_2$. For $s \geq s_2$, τ decreases linearly to the value of the ultimate frictional bond resistance τ_3 at a slip value of s_3. The behavior under cyclic loading is defined by the slope K of the unloading and reloading branches and by two damage factors, controlling the reduction of the reduced envelope in comparison to the monotonic envelope and of the frictional resistance. More details are given in /3,4/.

The analytical bond model can easily be extended to describe the behavior of a hook as observed in the tests. The hook is idealized as a straight bar with a length equal to the equivalent length l_d' (see Fig. 5) and the following values characterizing the monotonic and cyclic behavior are assumed:

For hooks bent against direction of casting: $s_1 = 1$ mm, $s_2 = 3$ mm, $s_3 = 100$ mm, $\tau_1 = 22$ N/mm², $\tau_3 = 4$ N/mm², $\alpha = 0.20$, K = 110 N/mm³, damage factors as for local bond model (see /3/).For hooks bent in the direction of casting the same values can be used, but with $s_1 = 2$ mm. They are valid for hooks of deformed bars with $d_b = 25$ mm, formed as shown in Fig. 1 and embedded in well confined concrete with a strength $f_c' \sim 30$ N/mm².

When modelling the hook behavior in this way, the existing computer program /4/ to calculate the behavior of long anchorages can be used to predict also the behavior of hooked bars under monotonic and random cyclic loading.

5 COMPARISON OF ANALYTICAL PREDICTION OF FORCE-SLIP RELATIONSHIP WITH EXPERIMENTAL RESULTS

The steel stress-slip relationships, obtained using the model described in section 4, are compared in Fig. 8 with experimental results for monotonic and cyclic loading obtained in the Berkeley tests. As can be seen, the agreement between prediction and experiment seems to be sufficient for practical purposes. In general the model was succesful in reproducing the main features of the experimental results.

6 CONCLUSIONS

From the results, obtained in this study the following observations can be made.

(1) The bond behavior of hooks embedded in well confined concrete is superior to the bond behavior of straight bars with a length equal to the distance between beginning of a hook and tangent at the hook

(1) Under monotonic loading the resistance of hooks after reaching the maximum value is almost constant over a large slip range

(3) Cyclic loading produces a significant deterioration of strength and stiffness of the anchored hook at slip values smaller than the peak slip values, between which the hook is cyclically loaded, but does not influence much the force-slip behavior at slip values larger than the peak values during previous cycles.

(4) The proposed model for the force-slip relationship provides satisfactory agreement with experimental results under various slip histories.

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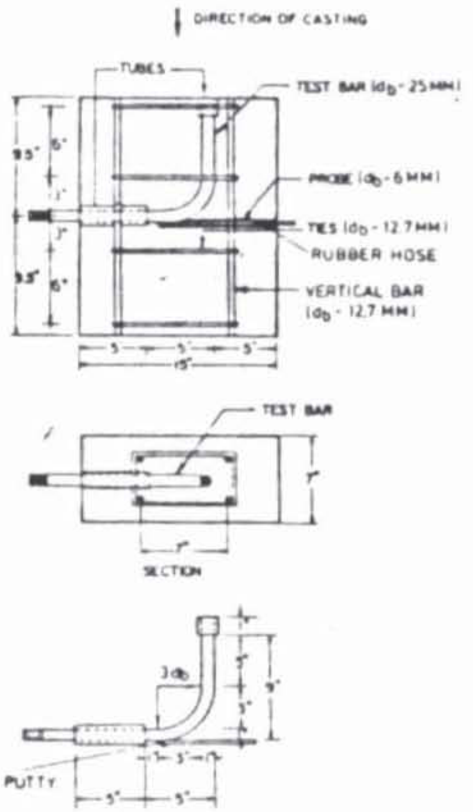

Fig. 1: Test specimen

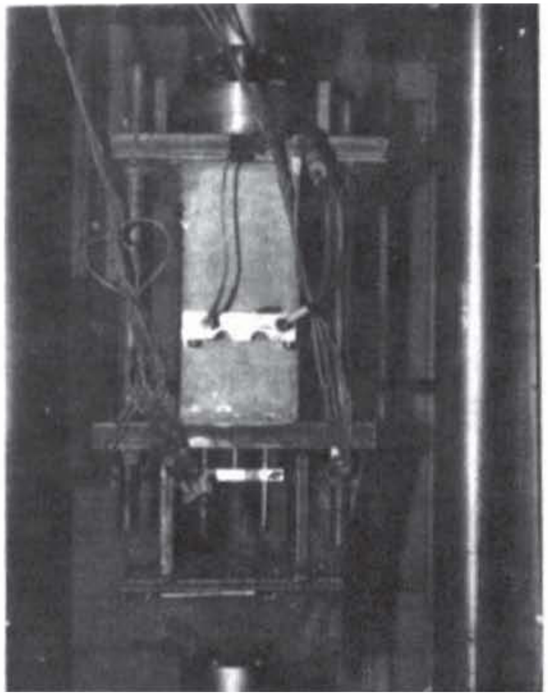

Fig: 2: Foto illustrating test setup

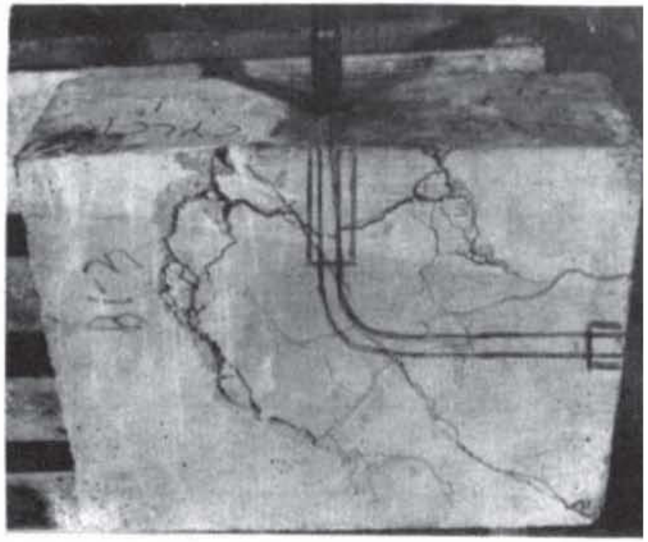

Fig. 3: Specimen after failure

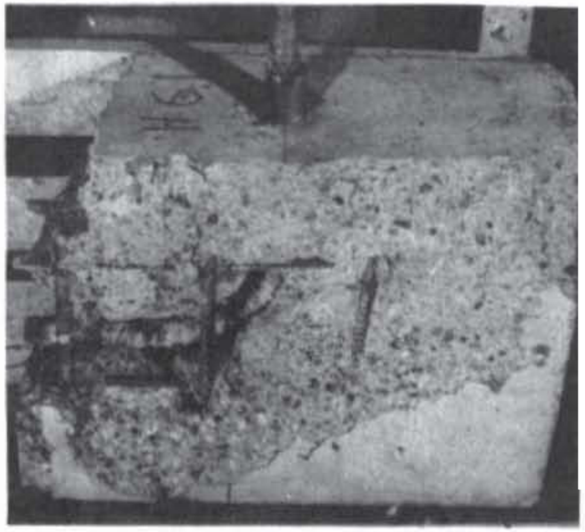

Fig. 4: Specimen after failure, loose concrete removed

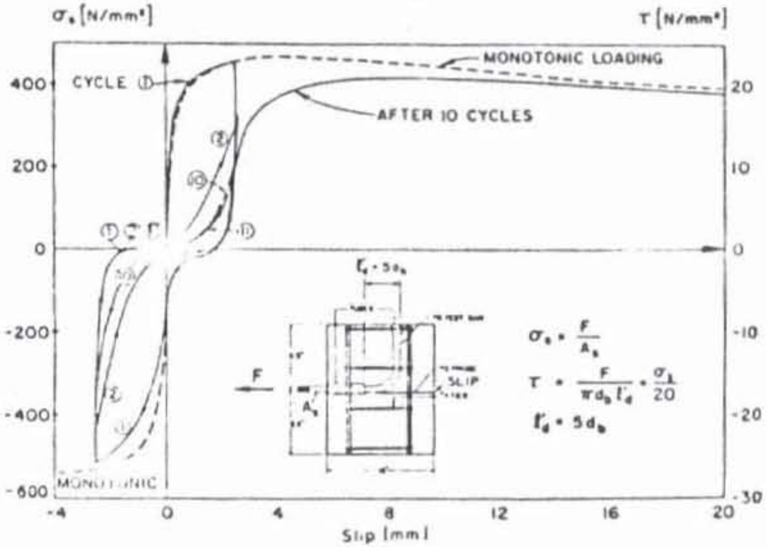

Fig. 5: Steel stress-slip relationships of hooks

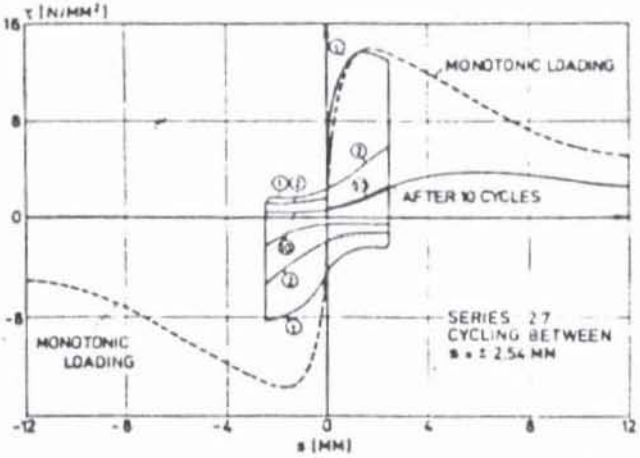

Fig. 6: Bond stress-slip relationships of straight bars

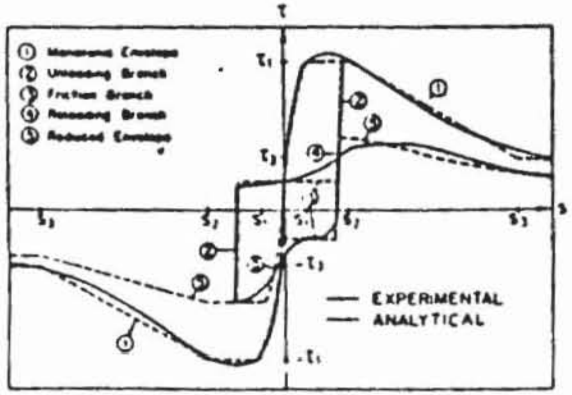

Fig. 7: Analytical model for local bond stress-slip relationships of straight bars

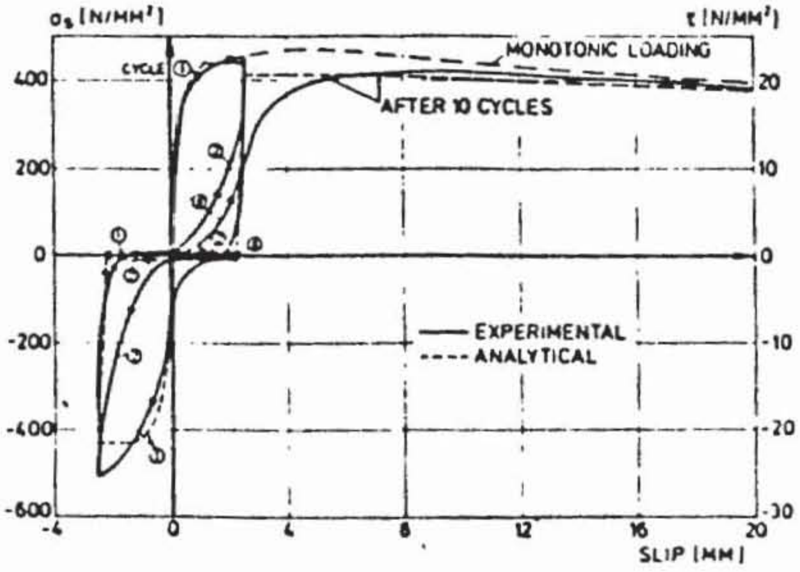

Fig. 8: Comparicon of experimental and analytical results on steel stress-slip relationships of hooks