Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.IV)

6-5-8

ASEISMIC BEHAVIOR AND DESIGN OF REINFORCED CONCRETE CORBELS

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SUMMARY

In this paper an experimental study is presented of the behavior of corbels subjected to both vertical and cyclic reversed horizontal loading, and based upon the study of the test data of 136 corbels the semiemperical equations for predicting their carrying capacity have been established, and from which the earthquake resistant design equation is derived.

INTRODUCTION

The reinforced concrete corbels projecting from the faces of columns to support the girders or roof trusses are the important parts of structures. Until recent years there has been little research available on their aseismic behaviors. This paper presents an experimental study on the ductility, strength and types of failure of corbels subjected to both vertical and cyclic reversed horizontal loading, and based on this investigation, the aseismic design of reinforced concrete corbels is proposed.

TESTS OF CORBELS

Scope of Tests Put to test were four series totalled 65 corbels specimens. The variables considered in the tests were ratio of shear span to effective depth (m), ratio of horizontal to vertical load (n) and main reinforcement ratio (μ). They are m=0.3, 0.6; n=0,0.3, 0.6, 1.0; μ=0.26%, 0.46%, 1.04%, 1.47%. respectively.

Test Specimens and Set Up The details of specimens are shown in Fig.1. The bearing plate was anchored by four bars under it, two vertically and two horizontally. The horizontal bars also function as main reinforcement. On top of the bearing plate two square bars were welded for imposing horizontal loads. A sufficient amount of horizontal stirrups (about 50% of the area of main reinforcement) distributed in the 2/3 of the effective depth, were provided to avoid diagonal splitting of the corbels. The cubic compressive strength of concrete varied from 215 to 313 kg/cm^2 and the yielding Strength of steel varied from 2675 to 4256 kg/cm^2.

The test set up is shown in Fig.2.

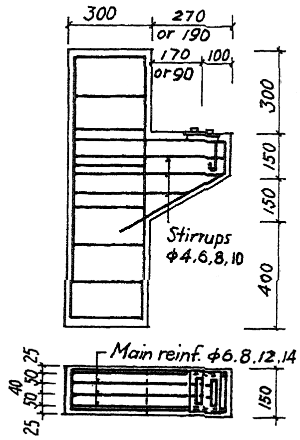


Fig. 1 Corbel Test Specimens

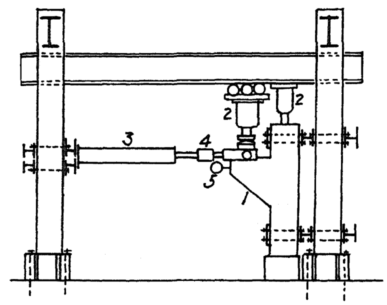


Fig. 2 Test Set Up
1-Specimen; 2-Oil jack; 3-Double acting ram; 4-Load cell; 5-Deform gauge

TEST RESULTS

The Behavior of Specimen

(1) Specimens subjected to both vertical and cyclic reversed horizontal loads

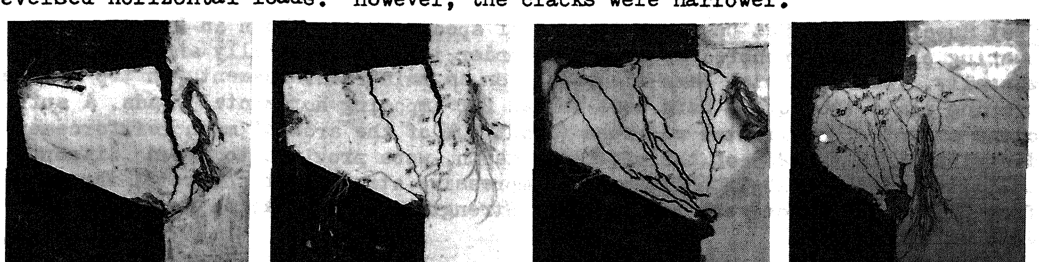
The cracks that firstly formed were flexural, propagating from the intersection of the column face and horizontal face of the corbel, and then the diagonal cracks followed, the development of which depending primarily on the reinforcement ratio, ratio of the shear span to the effective depth and ratio of horizontal to vertical loads.

The flexural tension failure took place with corbel specimens at low reinforcement ratio (0.26%, 0.42%). At the failure stage all the main reinforcement and stirrups within half depth of the corbel yielded, and the failure was characterized by very wide vertical cracks, as well as the crush of concrete at the bottom of the sloping face of corbel. In this case, the diagonal cracks did not even appear, as shown in Photo 1 (a), (b).

The shear compression or diagonal compression failure would took place with corbels at higher reinforcement ratio (1.04%, 1.47%). At the failure stage some of the reinforcement would yield or no one yielded. In this case, the vertical cracks did not develop so extensively, but the diagonal cracks developed rather thoroughly, and eventually, the corbel failed as the concrete at the root of the corbel was crushed, as shown in Photo 1 (c), (d).

(2) Specimens subjected to both vertical loads and monotonic horizontal pulls

The failure mode were the same with the corresponding corbels under cyclic reversed horizontal loads. However, the cracks were narrower.

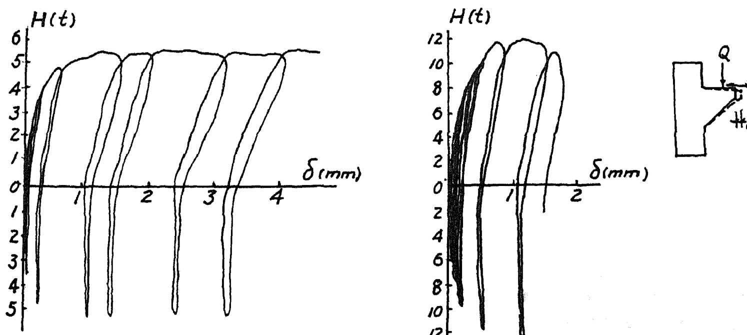


(a) (b) (c) (d)

Photo 1 Failure mode and cracking

Analysis on the Results of the Test

(1) The hysteresis loops for horizontal load versus displacement is shown in Fig.3. Fig.3 (a) shows the typical hysteresis loops for corbels failed in tension, and Fig.3 (b), in compression. It can be seen that the former is more ductile than the later. Tests indicated that the ductility factor in flexural tension failure varies from 6 to more than 20, and in compression failure from 3.3 to 6.3.



(a) (b)

Fig.3 Load-Displacement relationship for corbel

(2) Fig.4 shows the influence of the reinforcement ratio p', shear span to depth ratio m and the ratio of horizontal to vertical load n on the carrying capacity of corbel. The reinforcement ratio p' is defined as in Eq. (4)

(3) The carrying capacity of corbels subjected to combined vertical loads and cyclic reversed horizontal loads is 0.94~1.03 times that of corbels subjected to combined vertical loads and monotonic horizontal pulls with the average 0.97 for corbels failed in flexural tension. For corbels failed in shear compression it is 0.84 ~ 0.98, and the average is 0.94.

(4) The tests showed that under the joint action of vertical and horizontal loads the diagonal cracks often initiated at the inner edge of bearing plate, and they aligned with the direction of principal compression stresses. A curved arch thus formed, in which compression stress flow was concentrated. Hence, we can take the tied arch as the mechanical model as shown in Fig.5. In this tied arch the tensile strength of tie is equal to the resultant of the yielding strength of steels within half the depth of the corbel.

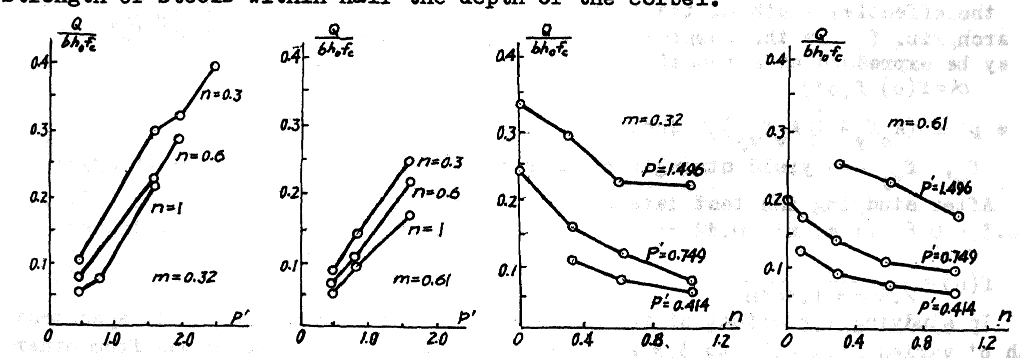


Fig.4 Corbel strength relating to the various parameters

According to the above model, the failure of corbels may be attributed to either the yielding of its tie, i.e, due to tension failure, or the crush of concrete at the critical section of arch rib near the root of corbel when it reaches its ultimate compression strength, i.e, due to compression failure.

a) Capacity of corbel failed in tension

From the equilibrium condition of the tied arch (Fig.5)

$\Sigma M = o$,

$Qc' + Hah_o' - Tah_o' = o$

Therefore

$$Q = \frac{T}{\frac{m'}{a} + n} \qquad (1)$$

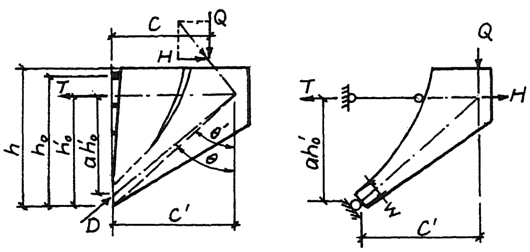


Fig. 5 Mechanical model

Where $T = A_s f_y + A_v f_{vy}$

A_s, f_y --- Area and yielding strength of main reinforcement steel;

A_v, f_{vy}--- Area and yielding strength of stirrups installed within $\frac{1}{2}h_o$;

$n = H/Q$, $m' = c'/h_o'$, $c' = c + (h - h_o')n$

The value a in Eq. (1) can be determined by the test. A statistical analysis was made for 42 specimens failed in flexural tension, The average value of a is $\bar{a} = 1.093$, and standard deviation is 0.1823.

Take $\bar{a} = 1.0$, Eq. (1) becomes

$$Q = \frac{T}{m' + n} \qquad (2)$$

Fig. 6 shows the comparison of the strength calculated by Eq.(2) with the test results. The average value of Q_t / Q_{cal} is 1.019, the coefficient of variation being 0.076.

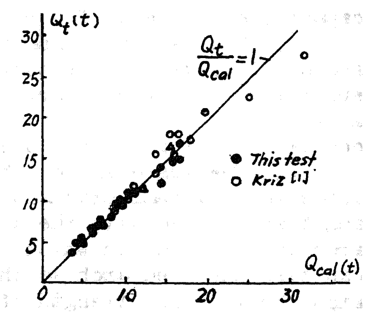


Fig. 6 Q_t/Q_{cal} for tension failure by Eq. (2)

b) The capacity of corbel failed in compression

The ultimate load of corbels failed in the crush of concrete can be expressed in terms of its vertical component as

$$Q_c = \alpha b h_o' f_c \cos\theta \qquad (3)$$

Where θ is angle between the vertical and the thrust D acting on the critical section of the arch rib. We can approximately take $\theta \approx \theta' = \tan^{-1} m'$ and $\cos\theta = 1 - 0.3m'$.

$\alpha = W/h_o'$ = coefficient of effective width, where W is the effective width of the critical section of the arch rib. f_c is the compressive strength of concrete. α may be expressed as a function of n and p'. That is

$$\alpha = f(n)\, f(p') \qquad (4)$$

Where $p' = (A_s f_y + \frac{2}{3} A_v f_{vy}) / 34bh_o$

f_y, f_{vy} --- yield strength of main reinforcement and stirrups in kg/cm^2

After studying the test data of specimens with $p' = 1.05$ and $n = 0 \sim 1.0$, $m = 0.3 \sim 0.6$ (i.e. $m' = 0.42 \sim 0.87$), the following equation is established

$$f(n) = \frac{1}{2.506 + 1.464n} \qquad (5)$$

In studying the effect of reinforcement ratio, the test data of 41 specimens with p' varies from 0.58 to 3.9 are analyzed. Part of the data comes from other investigations. The result is

$$f(p') = 0.4679 + 0.2667p' \qquad (6)$$

with standard deviation $S = 0.1380$ as shown in Fig.7, line a.

Hence

$$\alpha = \frac{0.4679 + 0.2667p'}{2.506 + 1.464\ n} \qquad (7)$$

Substituting Eq.(7) into Eq.(3). We obtain the formula for predicting the ultimate strength of compression failure of corbels as follows:

$$Q_c = \frac{0.1867\ (1+0.57p')}{1 + 0.5842\ n} \ (1-0.3\ m')bh_o'f_c \qquad (8)$$

The average value of Q_t / Q_{cal} is 1.049 and the coefficient of variation is 0.164.

c) The reinforcement ratio for balanced failure

Equating Eq.(1) to Eq.(8), the balanced steel content can be found as:

$$P'_{bal} = \frac{1.75\ k}{338(1+0.5842\ n)-k} \qquad (9)$$

Where $k = (0.915m' + n)(1-0.3m')f_c$

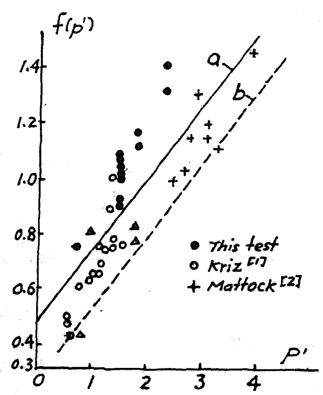


Fig. 7 p' - f(p') relationship

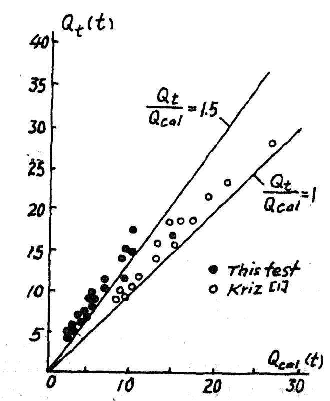


Fig. 8 Q_t/Q_{cal} for tension failure by Eq.(10)

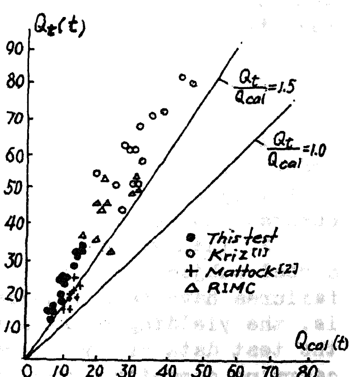


Fig. 9 Q_t/Q_{cal} for comp failure by Eq.(13)

THE PROPOSED METHOD OF DESIGN

The design procedure may be as follows

1. Selecting tentative proportions for the corbel.
2. Predicting steel area of main reinforcement.

In determining the steel area of corbels the horizontal stirrups may be neglected for simplicity. And take a = 0.85 in Eq.(1) on account of safety margin. Eq.(1) becomes:

$$Q = \frac{A_s f_y}{\frac{m'}{0.85} + n} \qquad (10)$$

From Eq.(10), considering $h_o' = h_o$, and $h_o \approx 0.9h$, we have

$$A_s = \frac{Q\ c}{0.85\ h_o f_y} + 1.1\ \frac{H}{f_y} \qquad (11)$$

Fig.8 shows the comparison between Q_t and Q_{cal} calculated by Eq.(10). It can be seen that the factor of safety of specimens in this investigation are larger than that of Kriz's. This is because there were no horizontal stirrups in Kriz's specimens.

3. Checking the rib strehgth

two different approaches are suggested as follows

(1) Method A

Subtracting 1.6s from $f(p')$ (Eq.6) on account of safety margin, yield

$f(p') = 0.2471 + 0.2666\, p'$

as shown in Fig.7, line b. Thus Eq.(8) will be reduced to

$$Q_c = \frac{0.0986(1+1.079\, p')}{1+0.5842\, n}\,(1-0.3\, m')\, bh_o' f_c \qquad (12)$$

Let $m' = 1.1$, the upper bound in practice, and $h_o' = 0.9h_o$, then Eq.(12) becomes

$$Q_c = \frac{0.06(1+p')}{1+0.6\, n}\, bh_o f_c \qquad (13)$$

Comparing Q_c calculated by Eq. (13) with the test data, the result is shown in Fig. 9.

(2) Method B

Control the reinforcement ratio so that the corbel will fail in flexural tension, for, as we know, this failure mode is favorable to earthquake resistance for its high ductility.

CONCLUSIONS

1. The reinforced concrete corbels in engineering practice behave ductilely under both vertical and cyclic reversed horizontal loads with the factor of ductility from 6 to 20 or more for flexural tension failure, and 3.3 to 6.3 for compression failure.

2. The tied arch is used as a mechanical model in predicting the strength of corbel subjected to both vertical and cyclic reversed horizontal loads. All failures have been considered as tension failure and compression failure, that is, the yielding of arch tie and the crush of arch rib. Based upon the study of the test data of 136 corbels the semiemperical equations for predicting their carrying capacity have been established, and from which the aseismic design equation was derived. These design equations may be applied to corbels within an range of $m=c/h_o= 0.2 \sim 1.0$, $n=H/Q \lesseqgtr 1$.

3. Two methods dealing with the compressive strength of the corbel are suggested: (1) checking the compressive strength, (2) controling the reinforcement ratio, so that the corbel will fail in tension. The second method seems more reasonable, so far as the earthquake resistance is concerned.

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