Finite Element Analysis of Reinforced Concrete Corbels

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Abstract:- In view of the increasing need of housing these days, the authorities in Malaysia have become interested to use efficient, faster and safer methods of building. One of such methods is by adopting Industrialized Building System (IBS) started in 2002. It was found from the last earthquake in Turkey that most collapse of precast buildings was caused by failure of connections. Therefore, an extensive research should be carried out to improve precast concrete connections. A common simple precast concrete connection is corbel. Reinforced concrete corbels are structural elements widely used in practice. The complex response of these elements is described in design codes in a simplified manner. These formulations are not sufficient to show the real behavior. Finite element models were carried out on *254 x 405 x 254*-mm reinforced concrete corbels. Ratio of primary and secondary reinforcement was varied. The results indicate that corbels with neither primary reinforcement nor secondary reinforcement fail suddenly and catastrophically. It seems that the mode of all failures was by diagonal splitting. Increase in ratio of primary and secondary reinforcement generally resulted in enhancement both strength and ductility of corbels. This increase also enhances the ultimate shear load until the ratio of primary and secondary reinforcement reach 0.35% and 0.30% respectively.

Key-Words: Precast Construction, Connection, Corbel.

1 Introduction

In reinforced concrete constructions, lateral loads, such as wind and earthquake loads are mainly resisted by shear walls and connections. Failure of precast constructions is mostly caused by connections, in which a corbel could be used. Corbels are widely used in precast concrete structures in view of the advantages such as; improved production speed and lower construction costs. During the past century, theories (Holnicki-Szulc & Gierlinski 1997, Ali & White 2001) have been proposed to describe corbel behavior, and several experimental studies have been carried out to investigate the behavior of corbels from the practical point of view. This paper aims to examine the load carrying capacity of reinforced concrete (RC) corbels with different ratios of primary and secondary reinforcement. Yong and Blaguru (1981) conducted experimental studies using normal-strength concrete and concluded that the shear strength is a function of: (1) shear span- to-depth ratio (2) reinforcement ratio (3) concrete strength and (4) the ratio of the horizontal to vertical components of the applied loads. It is widely assumed that reinforced concrete corbels are principally shear transfer device. Secondary reinforcements are normally used to improve their shear capacities and reduce the likelihood of sudden failure. However, contribution of stirrups has been shown to be variable when corbels are subjected to combined vertical and horizontal loads. Furthermore, most corbels containing stirrups as a secondary reinforcement fail in shear that displays no ductility. Also, distress of corbels in the field has been attributed to poor detailing of reinforcement. Such detailing may generally include bending and anchorage of reinforcement and cover to reinforcement. These difficulties may be accentuated by the use of stirrups (especially in small-size corbels), as a more complex detailing procedure is normally required. Additional secondary reinforcements would improve the cracking resistance of concrete, and modify or contain the explosive nature of high-strength concrete at failure.

2 Finite Element Modeling

With the development of high-powered computers, together with state-of-the-art finite element (FE) software and user-friendly graphical interfaces, three-dimensional (3-D) FE analysis has become a popular choice to predict the behavior of structural elements. Finite element software LUSAS version 14.1 has been used in this study. The mesh size of 30X30 mm was chosen based on convergence studies carried out to determine the optimal mesh that gives a relatively accurate solution and one that takes low computational time. It has been found that this mesh is capable of producing results close to the actual behavior of corbel connection. In this study steel was assumed to behave as an elastic-perfectly plastic material in both tension and compression. The idealized stress-strain curve used in the numerical analysis is shown in Fig. 1. The material properties of steel were specified using the elastic and the metal plasticity with plastic options. LUSAS requires input of the Young's modulus, E, Poisson's ratio, υ, and yield stress of steel, σ_y.

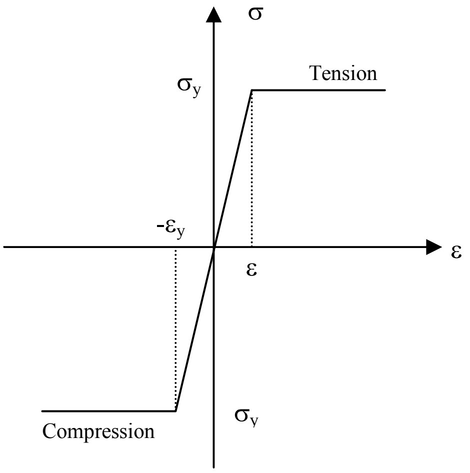

Fig 1 Stress-Strain Curve of Steel

Solid elements are capable of predicting the nonlinear behavior concrete. The element characteristic is able to describe elastic, isotropic, plastic and multi-crack concrete behavior. The Multi-crack concrete model is a plastic-damage-contact model in which damage planes form according to a principal stress criterion and then develop as embedded rough contact planes. Concrete is a quasi-brittle material and has different behaviors in compression and tension. The tensile strength of concrete is typically 8-15% of the compressive strength as shown below. Stress-strain relationship for concrete is shown in Figure 2.

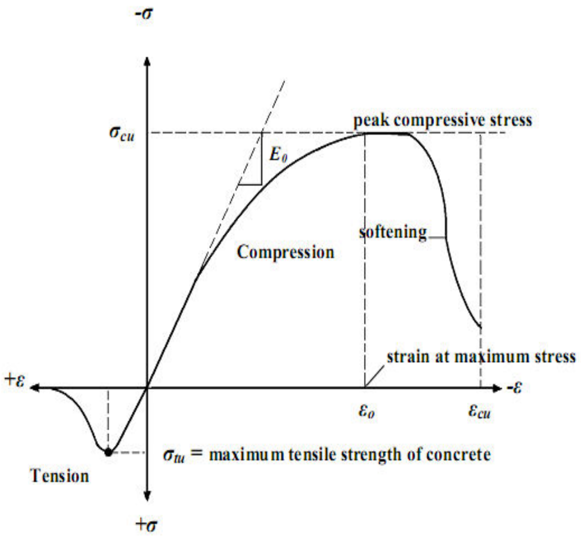

Fig 2 Stress-Strain Curve of Concrete from Damia

Seven specimens tested by Stephan (1996) were considered in this study to verify the modeling by LUSAS. All specimens were modeled and analyzed with LUSAS and the results presented in Figure 3. The results for ultimate load obtained from LUSAS are compared with the corresponding test results by Stephan (1996). It is found from the figure that the difference in ultimate load is less than 15 %. The difference could be attributed to the assumptions that were used in modeling the specimens. Since some of the properties are not given in the paper, reasonable assumptions were made to achieve close result between the simulation and the test results. The 45° line indicates the accuracy of the results thus results from LUSAS and those from the experiment would lie on the line if they match exactly. Since it has been found that the LUSAS model could predict the experimental results to an acceptable accuracy it has been decided to use LUSAS for further analyses.

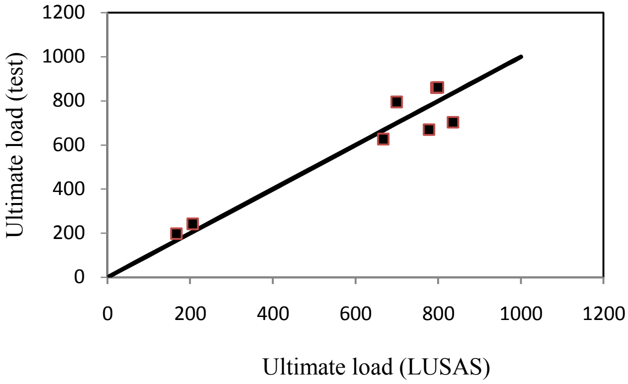

Fig 3 Comparison between finite element results and test results.

3 Details of Corbels Geometry and Reinforcement

As it is shown in Figure 4, the column supporting the corbel cantilevering on either side was 254 by 405 mm in cross section and 254 mm long. Column was reinforced with four 16-mm-diameter longitudinal bars and 9-mm- diameter stirrups spaced at 216 mm center to center as shown in the Figure 4. The load was gradually applied on either side of the corbels. The reinforcement details for the corbels are presented in Table 1. In Table 1, P represents the corbels that are associated with different primary reinforcement, and S represents the corbels associated with secondary reinforcement. For instance, P-0.15 represents a corbel in series P with 0.15 as the percentage of primary reinforcement (steel area of primary reinforcement over cross section).Two corbels without either primary reinforcement or secondary reinforcement were analyzed to study the behaviors. In Series P, the area of primary reinforcement was varied from 0 mm2 to 565.8 mm2, and the area of secondary reinforcement was kept constant. On the contrary, in series S, the steel area of primary reinforcement was kept constant, and the steel area of secondary reinforcement was varied from 0 mm2 to 257.2 mm2.

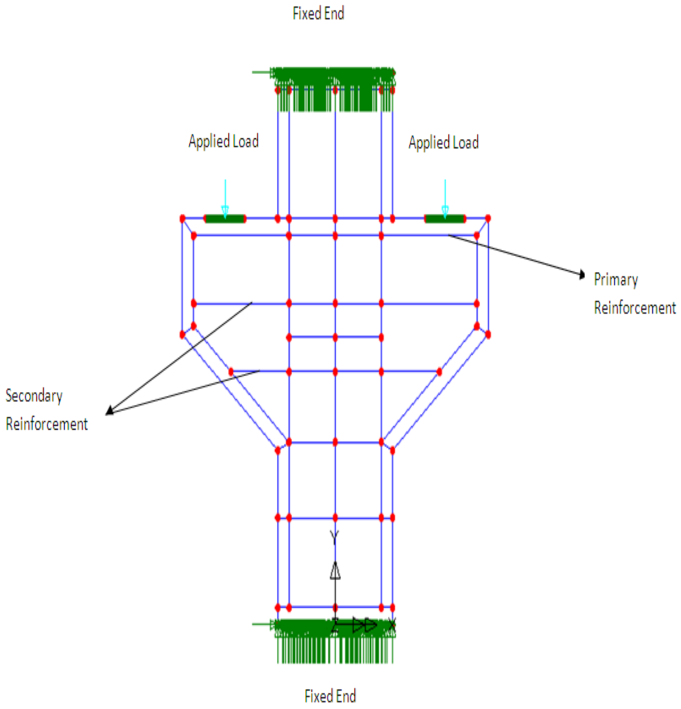

Fig 4 Reinforcement Detailing

Table 1 Details of Corbels

Designation	Steel Area (mm^2)	
	Secondary Reinforcement	Primary Reinforcement
P-0	127.2	0.0
P-0.15	127.2	154.3
P-0.20	127.2	205.7
P-0.30	127.2	308.6
P-0.35	127.2	360.0
P-0.40	127.2	411.5
P-0.45	127.2	462.9
P-0.50	127.2	514.4
P-0.55	127.2	565.8
S-0	0.0	265.2
S-0.15	77.2	265.2
S-0.20	102.9	265.2
S-0.30	154.3	265.2
S-0.40	205.7	265.2
S-0.45	231.5	265.2

4 Finite Element Analyse of the Corbels

The finite element program LUSAS version 14.1 was employed to simulate the behavior of the corbels. In all these models the boundary conditions at the top and bottom of the column were assumed fixed and the load was applied incrementally on a bearing pad made of steel as shown in the Figure 4. Bearing pad was used to prevent local crushing of concrete. Except the ratio of primary and secondary reinforcements, details of all the models were kept the same. For each specimen, only a quarter of the specimen was modeled in view of the symmetry, in respect of geometry, loading and support conditions. Typical finite element model is shown in the Figure5. Analyses were carried out on each of the models and the results presented in the form of load-displacement plots as shown in Figures 6 and 7. Displacements plotted on the horizontal axis correspond to those measured under the load.

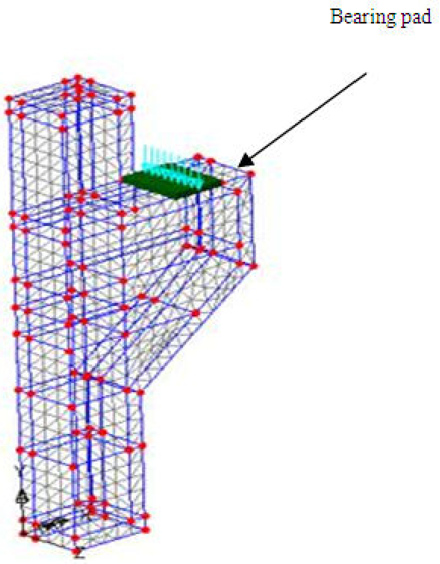

Fig 5 A Quarter of Meshed Corbel Model, using LUSAS.

5.1 Series P

Fig 6 shows load-deflection curves for Series P. Addition of primary reinforcements to corbels enhance the ductility and toughness. However, the degree of enhancement was more evident in corbels reinforced with lower ratios of main bars. It can be seen that the improvement of load carrying capacity of corbel is not significant for reinforcement ratio 0.3 and after. As predicted, corbel P-0 fails catastrophically in brittle manner. The results of series P is tabulated in Table 2. The results show that by increasing the percentage of primary reinforcement steel, the ductility increases, but are mostly attributed to up to 0.45%. As expected, ultimate load carrying capacity of the corbels is improved by increase in percentage of primary reinforcement steel, even though it is mostly attributed for lower ratios of main reinforcement.

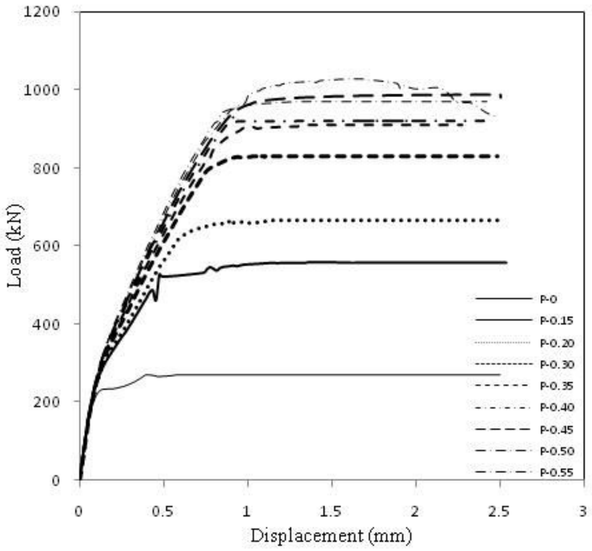

Figure 6: Load Deflection Curve Series P

Table 2 Corbel Series P Test Results

Designation	Ultimate Shear Load(kN)	Percentage Increase of Ultimate Load	Free End Deflection at Ultimate Load (mm)
P-0	272	0.0%	0.42
P-0.15	557	104.9%	0.45
P-0.20	667	145.2%	0.89
P-0.30	736	170.5%	0.94
P-0.35	829	204.7%	1.01
P-0.40	930	241.9%	0.91
P-0.45	989	263.5%	1.09
P-0.50	970	256.5%	1.28
P-0.55	1029	278.2%	1.66

5.2 Series S

The effect of addition of secondary reinforcements on the behavior of corbels, are summarized in Table 3. Load-deflection curves for corbel series S are shown in the Figure 7 in all corbels, it seems that the first cracks to appear were flexural cracks starting at or near the junction of the tension face of the corbel and face of the column. The result in Table 2 shows that the presence of additional secondary reinforcement resulted in an increase in load-carrying capacity and ductility of corbel. Corbels S-0 with no secondary reinforcement, failed in an explosive manner. The increase in load-carrying capacity of corbel is significant until the percentage of secondary reinforcement reaches to 0.3%. As expected, ultimate load-carrying capacity of corbel is improved by increase in percentage of secondary reinforcement steel, even if it is mostly pronounced for lower ratios of reinforcement. Increase in percentage of secondary reinforcement would influence in the resistance of corbel to lateral load.

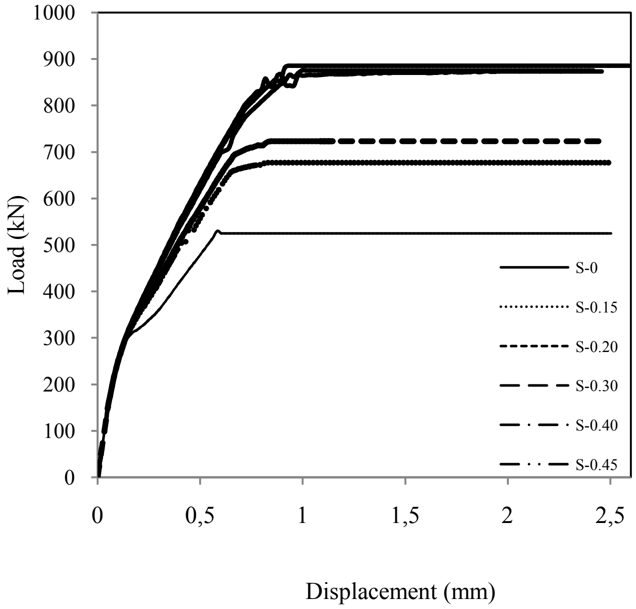

Fig 7 Load Deflection Curve Series S

Table 3.Corbel Series P Test Results

Designation	Ultimate Shear Load(kN)	Percentage Increase of Ultimate Load	Free End Deflection at Ultimate Load (mm)
S-0	530	0.0%	0.58
S-0.15	677	27.7%	0.83
S-0.20	724	36.4%	0.85
S-0.30	770	45.0%	0.95
S-0.40	876	65.1%	0.99
S-0.45	886	67.0%	0.93

6 Conclusions

The following conclusions can be drawn based on the results:

1-The failure mode of corbels with neither secondary reinforcement nor primary reinforcement was brittle and explosive.

2-Ultimate load-carrying capacity of corbel is improved by increase in percentage of primary reinforcement steel, although it is mostly pronounced for lower ratios of main reinforcement, nevertheless, causes an increase of ductility.

3- The load-carrying capacities of corbels are considerably enhanced by the addition of secondary reinforcements. The enhancement is noticeable until the percentage of secondary reinforcement reached to 0.3%.

4- As high strength concrete fails in brittle manner, and when it comes to corbel, secondary reinforcement would enhance the ductility of corbel.

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