Beam-column connection for precast concrete structures with high-performance concrete components

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Summary

This paper presents a proposal for beam-column connections in precast concrete structures using high-performance concrete components. The corbels can be formed by inserting components into the column pocket or the components may be employed as dapped-end beams at the ends of the precast beams. Diverse ways to use this connection in precast concrete skeleton structures are discussed. The study investigates the behavior of corbels made from fiber-reinforced concrete with up to 1.86% steel fibers and a compressive strength of up to 71 MPa. Two specimens were tested, each with a part of the column and a precast element forming symmetrical corbels. The results indicated that 1.86% of steel fibers could replace the secondary reinforcement of the corbel. The paper also discusses the relevant aspects, limitations, and precautions of this proposal, aiming to improve beam-column connections in precast concrete skeleton structures for multistory buildings.

Keywords: Precast concrete, Industrialized construction, Corbel, Steel fiber-reinforced concrete

1 INTRODUCTION

Quality control and ease of manufacture are characteristics of precast concrete structures. However, the necessity to establish connections among the components is a difficulty when precast concrete elements are used. In general, the connections are the most important parts in the design of precast concrete structures. They are of fundamental importance both for production - which includes the manufacture of part of the elements adjacent to the connections, the assembly of the structure and the execution of the connections themselves - and for the behavior of the final structure, as well as for maintenance. Therefore, the utilization potential of precast concrete increases as the connections between the components are enhanced, both in terms of feasibility and structural behavior, as well as for maintenance.

In multistory buildings, beam-column connections are the most important connection due to the number of repetitions and their role in structural behavior. Therefore, the development of new possibilities and improvements to column-beam connections is important to increase the use of precast concrete in multistory buildings with a skeleton structural system.

The objective of this paper is to present a proposal for a column-beam connection utilizing high-performance concrete components, with a focus on applications in skeleton structures for multistory buildings. The relevant aspects of this proposal are presented, as well as the limitations and precautions involved in their use. The objective of this paper is to investigate the behavior of the corbel. For this purpose, two specimens were tested, each with a part of the column and a precast element that was inserted into the pocket of the column to form two symmetrical corbels. Fiber-reinforced concrete with up to 1.9% steel fibers and a compressive strength of up to 70 MPa was used for the corbel.

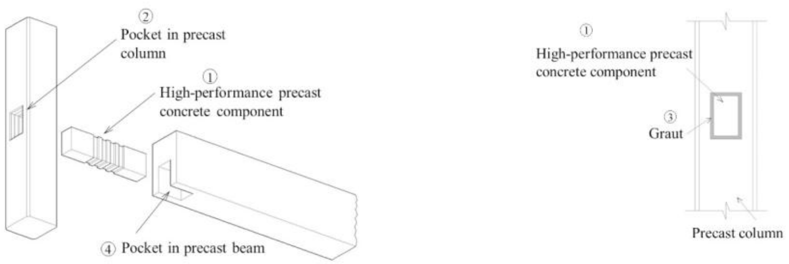
2 DESCRIPTION OF THE BEAM-COLUMN CONNECTION

The proposal is based on the use of prefabricated high-performance concrete components for the manufacture of corbels and dapped-end beams. The concept of high-performance concrete is not well-defined. In general, it is associated with high-strength concrete. Some properties, such as durability, are improved by the increase in compressive strength due to protecting the reinforcement from corrosion. However, the enhancement of the material's strength results in its fragility, which can be mitigated by incorporating short fibers.

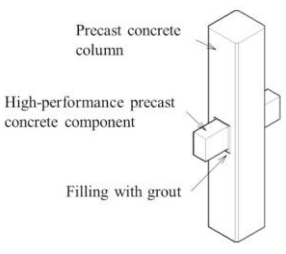
In this proposal, concrete has a compressive strength of 50 MPa or greater and is reinforced with steel fibers to reduce the reinforcement ratio in the components. These components are separately manufactured from the beams and columns. The schematic representation of the described parts of the connection and the steps involved in its manufacture are shown in Fig. 1.

In general terms, this proposal can be summarized as:

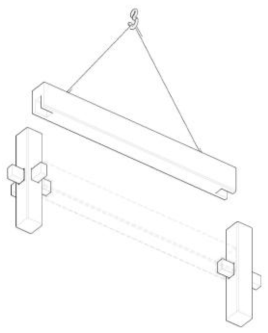
- The use of high-performance concrete precast component (component 1), with a high steel fiber reinforcement content, and continuous reinforcement, as corbel.
- Making a pocket in the precast column (component 2) to receive the high-performance concrete (HPC) precast component.
- Fixing the HPC precast component to the precast column with grout (component 3) injected to fill the space between the two components, either in the factory or on site. The use of shear keys, both in the beam and the column pocket, provides the appropriate conditions for securing the HPC precast component.
- A pocket at the end of the precast beam (component 4) serves to support the beam on the corbel fixed to the column, to hide the connection.



a) Connection components



b) Column with grouted corbels

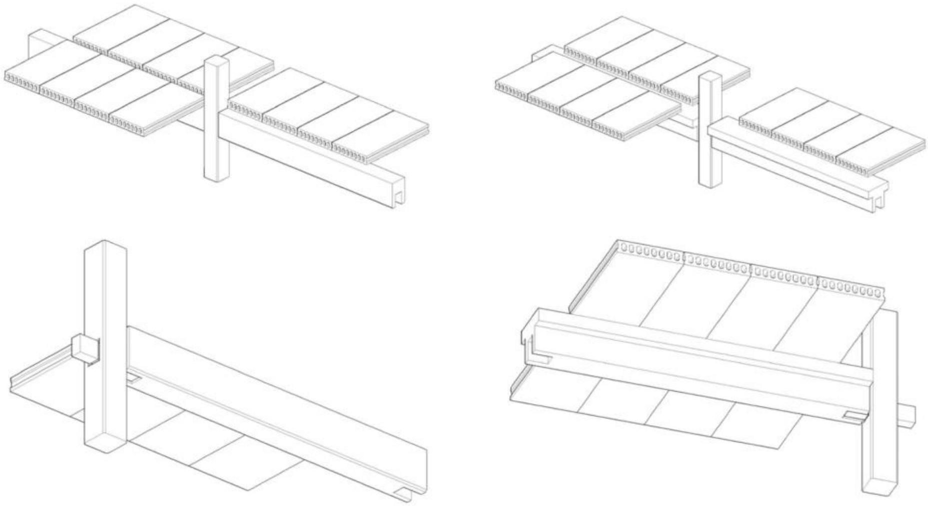


c) Beam assembly

Fig. 1 Schematic of the proposed connection

Fig. 2 shows the schematic of the floor with the connection, using a rectangular beam and a T-section beam. The idea of using high-performance concrete for connections in precast concrete structures has been around for many years. However, high-performance concrete components cast at distinct stages of the precast structural elements for use as corbels in connections have been studied more recently [1].

The use of steel corbels placed before or after the casting of precast structural elements also exists. The innovation of this proposal is based on the use of a prefabricated component with high-performance concrete fixed in pockets in the precast columns to form corbels.

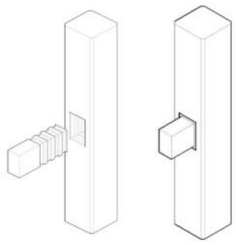


a) Rectangular beam b) T-section beam

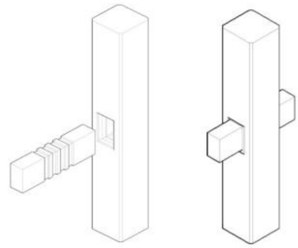
Fig. 2 Schematic of the floor with the proposed connection

It is possible to place corbels on the various sides of the columns, with some variations. A column with a corbel on only one side or two corbels on opposite sides can be done with a single prefabricated component coming out of the column (Fig. 3a and Fig. 3b). On the other hand, a column with corbels on three sides can be executed as shown in Figure 3c, wherein a prefabricated component with holes is initially positioned in one direction, followed by another prefabricated component with steel bars, which corresponds to the continuous reinforcement. These bars are fixed to the first component with nuts and washers to ensure their anchorage. The case of a column with corbels on all four sides can be handled according to the schematic in Fig. 3d, which is similar to the previous one, with the bars protruding from the second prefabricated component with great length and the corbel on the fourth side being cast with high-performance concrete.

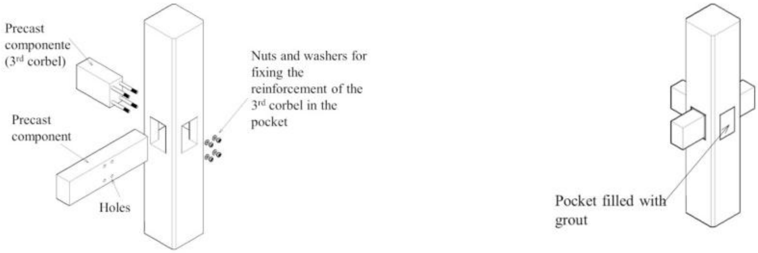
The steel bolt can be used to connect the precast corbel to the precast beam. By grouting the steel bolt and the space between the beam and column, a semirigid connection can be achieved, capable of partially transferring positive and negative bending moments. Precast high-performance concrete components can also be used in precast beams. These components, known as dapped-end beams, would allow for the use of high-performance concrete at the ends of precast beams. The beams would be cast using dapped-end beams with high-performance concrete placed at their ends, with the lap splice of the longitudinal reinforcements.



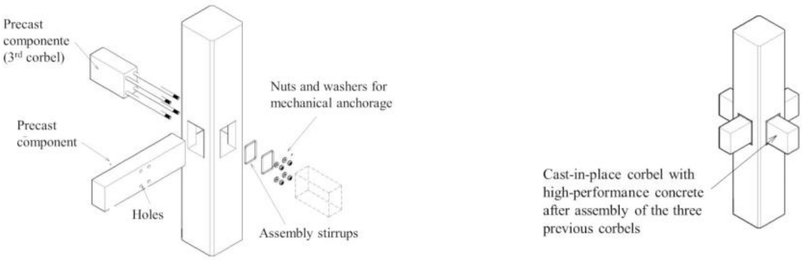
a) Column with one corbel



b) Column with two corbels



c) Column with three corbels



d) Column with four corbels

Fig. 3 Schematic for making corbels on four sides of the column

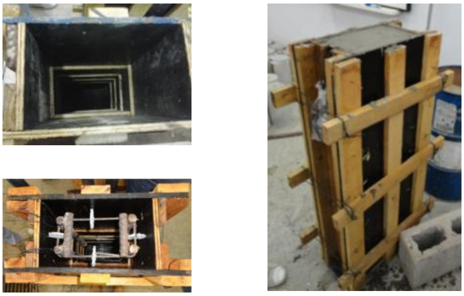
3 TEST IN HIGH-PERFORMANCE CORBEL

3.1 Specimen geometry

In this paper, a preliminary study of the connection was conducted, and two specimens were evaluated. The specimen included a representative part of the column and an HPC precast component, forming a symmetrical model with two corbels. Therefore, the primary focus of this preliminary investigation was on the behavior of the corbel and its impact on the precast column.

The HPC corbel had a rectangular section with a length of 1000 mm, a width of 160 mm, and a height of 260 mm. The corbel region embedded in the column had shear keys with a depth of 10 mm and a width of 50 mm on all faces. The corbel reinforcement consisted of two 20 mm diameter bars anchored by a welded crossbar, forming a main tie. The corbels did not have any stirrups or secondary reinforcement.

The columns were of a cross-section of 400 mm x 400 mm and a height of 1000 mm. The column was executed with a 200 mm wide by 300 mm high pocket to allow for the precast corbels to be inserted later. The interior of the pocket contained shear keys of identical dimensions to the corbels. The corbel was fixed to the column by filling the space between the pocket and the corbel with cementitious grout with a strength of more than 40 MPa at 7 days. Fig. 4 illustrates the production process for the specimens.



a) Cast the corbel with SFRC

b) Prefabricated HPC corbels

c) Shear key inside the column's pocket

d) Connection between corbel and column using grout

Fig. 4 Specimen assembly sequence

3.2 Materials

Table 1 shows the composition of the mix used to produce HPC corbels with steel fibers, which were of the RC Dramix® type with a length of 35 mm, diameter of 0.55 mm, aspect ratio of 65, and hooked ends. According to the manufacturer, this steel fiber had a strength of 1150 MPa. Two quantities of steel fibers were added to the concrete, 1.86% in specimen M01 and 0.65% in specimen M02.

The reinforcement steel used in the corbels was characterized and had a yield strength, $f_{y,}$ of 562.46 MPa. The modulus of elasticity, E_s, was assumed to be 200 GPa.

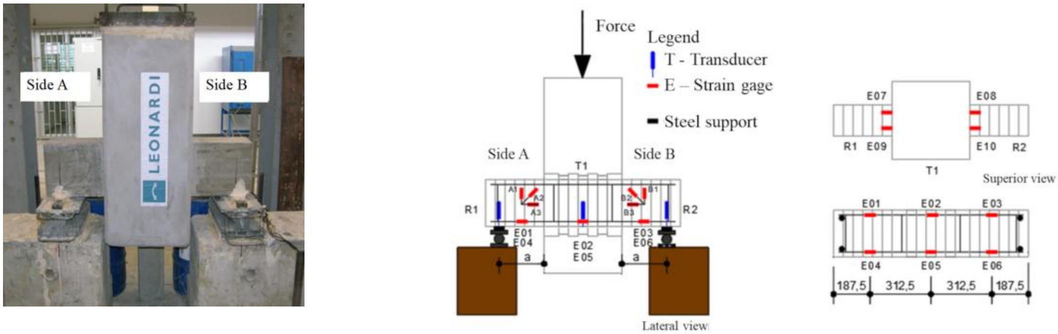
Table 1 Proportion of materials used to produce HPC corbels M01 and M02, in kg/m³.

Speci-men	Cement CP II-32	Artifi-cial sand	Natural sand	Coarse aggregate (D_{max} = 12.5 mm)	Super plasticizer	Micro ex-pander Dry one	Steel fiber	Water
M01	508.38	302.61	464.92	842	5.08	14	133.95 (1.86%)	200.15
M02	508.38	302.61	464.92	842	5.64	14	46.92 (0.65%)	200.15

3.3 Methods

The steel fiber-reinforced concrete was characterized by compressive strength, f_{cm} [2], splitting tensile strength, $f_{ctm,sp}$ [3], residual tensile strength, f_R [4] and modulus of elasticity, E_{cm} [5]. All specimens were kept in a humidity chamber, with a humidity of 99% and a temperature of ±20ºC, until the specimen was tested.

The specimens were simply supported, that is, one fixed and one moving support was used to avoid horizontal external loads. The width of the steel supports was 50 mm. The distance from the axis of the support to the vertical face of the column was 190 mm, resulting in *an a/d* ratio of 0.88. The main tie reinforcements were instrumented with strain gages to measure the strain during the test. Fig. 5 shows the final specimen and test setup, as well as the instrumentation used in the test.



a) Specimen under test b) Test setup and instrumentation

Fig. 5 Test setup and instrumentation

3.4 Analysis of results

Table 2 shows the mechanical properties of the fiber-reinforced concrete used in the HPC corbels. The columns had a compressive strength of 52.94 (± 2.40) MPa at the time of testing. It can be seen that the fiber volume influenced the compressive strength, which increased by 27% when the fiber volume increased to 1.86%. The compressive strength of both HPC corbels exceeded 50 MPa.

Table 2 Average values of the mechanical properties of steel fiber-reinforced concrete

Specimen	f_{cm} (MPa)	$f_{ctm,sp}$ (MPa)	E_{cm} (GPa)	f_L (MPa)	f_{R1} (MPa)	f_{R2} (MPa)	f_{R3} (MPa)	f_{R1}/f_L	f_{R3}/f_{R1}
M01	70.91 (± 2.11)[a]	10.33 [b]	33.63 [b]	19.10 [b]	17.17 [b]	19.10 [b]	17.93 [b]	0.90 [b]	0.94 [b]
M02	56.01 (± 2.54)[a]	8.51 (± 0.99)[a]	32.26 (± 0.72)[a]	8.23 (± 0.92)[a]	8.18 (± 0.92)[a]	5.41 (± 0.66)[a]	3.58 (± 0.43)[a]	0.99	0.44

[a] Standard deviation from three samples. [b] Values obtained from one sample.

The Model Code 2020 [6] indicates that steel reinforcement can be completely or partially replaced by steel fibers if $f_{R1k}/f_{Lk} > 0.4$ and $f_{R3k}/f_{R1k} > 0.5$. Considering the values in Table 2, these limits were satisfied in the concrete of specimen M01 with 1.86% steel fibers. In concrete specimen M02, with 0.65% steel fibers, only the f_{R1}/f_L ratio was satisfied, both for average values and for characteristic values. However, the f_{R3}/f_{R1} ratio was close to the limit, indicating that the steel fibers in this specimen could also replace the corbels secondary reinforcement.

The specimens M01 and M02 showed shear failure in the direction of the compression strut. In specimen M01, the shear cracks were observed at 32% of the yield strength of the man tie, with a force of 85 kN. In specimen M02, the shear cracks were observed at 54% of the yield strength of the main tie, with a force of 140 kN. The cracks in specimen M01 at a lower force are because it was harder to compact the concrete in this corbel because of the high volume of fibers. No concrete crushing was observed near the upper face of the corbels in the nodal region. Fig. 6 illustrates the cracking pattern. The ultimate resistance of M01 and M02 specimens was 331 kN and 299 kN, respectively.

a) Specimen M01 - Side B

b) Specimen M02 - Side B

Fig. 6 Shear failure and cracking pattern of the corbels

Fig. 7 shows the average force-strain curves of the main ties in specimens M01 and M02. It can be observed that the main ties in both specimens reached the yield strain of the steel (ε_y = 2.8‰) before the corbel failed in shear. In specimen M02, the ultimate force was 14% greater than the yield strength of the main tie, whereas in corbel M01, the ultimate force was 21% greater than the yield strength of the main tie. This indicates an increase in ductility with a larger volume of steel fibers.

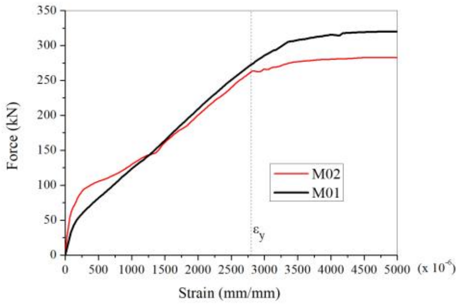


Fig. 7 Average force-strain curves of the tie rods of specimens M01 and M02

Table 3 shows the predicted force relative to the yield strength of the main tie and the ultimate resistance of the compression strut, calculated using normative and analytical equations. It is observed that the force relative to yield strength of the main tie varied from 290.9 kN to 362.3 kN using the equations presented in standards [7], [8], [9], with a difference of up to 40% in relation to the average experimental value (259.25 kN). The best approximation was obtained by the equation presented in EN 1992-1-1:2004 [8], using the methodology described in [10], with a difference of 12% compared to the experimental value. However, the ultimate resistance predicted by normative models was almost three times higher than the values obtained experimentally, indicating that these normative models are not suitable for predicting the ultimate resistance of the types of HPC corbels analyzed in this study. This is because the failure of the corbels was characterized by the formation of a shear crack, not a crushing of the compression strut.

Table 3 Predicted resistance of specimens M01 and M02

Specimen		Experi-mental (kN)	NBR 9062 (kN) [7]	EN 1992-1-1 (kN) [8]	PCI (kN) [9]	Fattuhi (kN) [11]
M01	Yield strength of the main tie (F_y)	260.56	362.3	294.8	359.5	366.7
	Ultimate resistance (F_u)	330.90	619.5	574.0	882.6	366.7
M02	Yield strength of the main tie (F_y)	257.93	362.3	290.9	350.6	349.9
	Ultimate resistance (F_u)	299.45	489.3	403.2	697.2	349.9

The ultimate resistance predicted by the analytical model proposed by Fattuhi [11] was a maximum of 17% different from the ultimate force of the corbel obtained experimentally. This model provides a unique resistance for the corbel, as it integrates the ultimate resistance of the compression strut and the yielding of the main tie into a single equation. It proved to be the most suitable for evaluating the ultimate resistance of the HPC corbel tested in this paper.

4 CONCLUSION

The main advantages of the connection proposal presented are that the columns can be made with metal formwork without cut-outs, which makes it possible to position the corbels in any position, and that the connection can be hidden. Moreover, there is the possibility of making a semirigid connection using steel bolts and grouting, with little fieldwork. However, there are some precautions, the main one being that the column must be dimensioned considering the reduced section in the position of the connection during handling. Additionally, confinement reinforcement must be provided in the column in the region of the connection.

The tests showed that increasing the volume of steel fibers to 1.86% resulted in a significant increase in the residual strength and ductility of the concrete. For this volume of fibers, the minimum values of the f_{R1}/f_L and f_{R3}/f_{R1} ratios established by the Model Code 2020 [6] were satisfied, indicating that it is possible to replace the secondary reinforcement with steel fibers. In fact, the ultimate force in this corbel was 21% higher than the yield strength of the main tie.

The best force relative to yield strength of the main tie was obtained using the equation from EN 1992-1-1:2004 [8] and modifications presented in [10], with a 12% difference from the experimental value. The ultimate resistance, however, was best estimated by Fattuhi's model [11], developed for corbels with SFRC, with a maximum difference of 17% from the experimental result.

Acknowledgements

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