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Nonlinear FE analysis of slab-beam-column connection in precast concrete structures

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ABSTRACT

In this paper, a nonlinear finite element analysis of slab-beam-column connection in precast concrete structures is presented. The detailed experimental results of the full-scale connection have been discussed in a different paper. However, due to the complexity of slab-beam-column connection and the unique features of the tested specimen, the numerical study was carried out to better understand the structural behavior. The internal connection was comprised by corbels, dowels and a continuity bars passing though the column. The FE model was validated using the experimental results of the precast concrete connection and it showed good capacity to represent the behavior observed in laboratory. A parametric analysis was conducted with the variation of the diameter of the continuity bars and the properties of the cast in place concrete. As a result of this study, some information about stresses, strains and displacements not obtained experimentally was determined in the numerical simulation and, with the parametric analysis it was concluded that the diameter of the continuity bars had more influence in the precast concrete connection capacity than the concrete compressive strength.

1. Introduction

Structural systems based on precast concrete elements have been built to be safe, durable, reliable and cost effective. A precast concrete structural system offers many advantages over in-situ casting. For instance, greater control over the quality of materials and workmanship, improved health and safety and cost efficiency are all realized through the off-site production of structural elements. As a result, a large number of research has have been conducted into their performance.

A special attention has to be given to the global stability in the design of precast structures due to the presence of the connections, which are the structure discontinuity points. Several experimental and analytical studies have been conducted in order to analyze, to classify and to determine the stiffness of the connections as well as to propose connections with different configurations. Some results showed that these systems could be considered as semi-rigid connections because there was transfer of moment from the beam to the column [1–3].

The use of prototypes in real scale in beam-column connections' tests is usual in reputable research centers. These tests are interesting because they allow the determination of the connection's stiffness that can be used in the design of this connection. In [1] it was studied the behavior of a trivial slab-beam-column connection with continuity reinforcement passing through the column and corbels with dowels. The use of corbels and dowels is usual in beam-column connections belonging to precast concrete structures due to the slippage prevention and the tensions transfer [4–7].

The use of continuous columns with a free space in the connection zone is another way to connect the vertical component to the beams [8–10]. This type of connection does not need corbels or dowels to put the elements together, but there is the disadvantage of using large quantities of cast in place concrete.

Focusing on the speed of construction provided by precast concrete, an advantageous association would be with steel elements. In [3] it was proposed a beam-column connection between steel column with steel corbel and precast concrete beam. Composite connections between steel and concrete elements using steel shapes and angles have been extensively studied [11–13]. The results showed that the connection gives satisfactory flexural performance, even though there is no presence of corbels and dowels too. The main purpose of the development of innovative configura-

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tions of connections is to make easier the assembly of the structure and to increase the stiffness.

The numerical analysis has been increasingly used to study the behavior of structures with some degree of nonlinearity [11,14–17]. In [17], the authors presented a numerical studied on the behavior of a beam-column connection without the slab contribution and with bars passing through the column, similar to the connection studied in this paper. The correlation with experimental results was satisfactory, validating the model and the numerical analysis. Large structures, which previously could only be studied with the use of models on a small scale, now can be analyzed with the real dimensions using the computing resources. Thus, the use of the numerical modeling as a way to complement the experimental analysis, or replace it, has become common in academia. With technological development, the numerical analysis has advanced a lot in describing the behavior of structures. One of the tools used in this case is the Finite Element Method (FEM) with the consideration of the materials' rupture models. The material model has a great influence on the quality and accuracy of results obtained from numerical analyses. The uniaxial compressive and tensile stress-strain curve is important to represent the structure behavior.

Formerly the precast buildings were design with pinned connections, which produce structures subject to large bending moments. In general, the connections between precast elements do not behave exactly as they are considered in the structural analysis. The designers consider that the connections allow or prevent entirely the relative displacements between the connected elements, which do not happen. According to Eurocode 3 [18], it is important to consider the real behavior of the connection, which usually fall between these two extreme cases. What happens is that the connections have an intermediate behavior and must be called as semi-rigid. However, with the conduct of research in the development of moment-resistant beam-column connections, the semi-rigid connection has emerged to improve the performance of precast concrete structures.

Due to the various configurations of moment-resistant connections and the large number of the developed classifications, Eurocode 3 [18] has a classification system for these connections in order to facilitate its use in civil engineering. Three types of classification for connections are presented: (a) rigid, (b) semi-rigid and (c) pinned. This classification recognizes that the large variation in the behavior of semi-rigid connections depends if the structure is bracing or not. Thus, it has two different classification systems: one for bracing structure and other for non-bracing.

2. Experimental study

In the past decades the incorporation of semi-rigid behavior into precast connection design has attracted attention, due to the large variety of connection configurations possible, the geometrical discontinuities, the stress concentrations and the presence of frictional forces that lead to nonlinear phenomena. These connections exhibit an overall nonlinear structural behavior classified as "semi-rigid". The joint of interest in this research is a type of slab-beam-column connection with continuity rebars passing through the column, which exhibit a semi-rigid behavior. Details of the experimental study addressed in this paper are presented in [1].

The specimen had a cruciform arrangement, which simulates an internal slab–beam–column connection in a semi-rigid frame. The specimen was assembled with two beams, hollow core slab and one column with corbels to comprise the cruciform arrangement. The corbels were on the ground, because it was not the intention of this research to analyze their behavior. This subject has been addressed in several studies as [5] and [7] by carrying out numerical simulations and reliability analysis. The beams were resting on corbels and dowels were used to ensure no slip. The behavior of the dowels was investigated in [4] where a complex model of a beam-to-column dowel connection was presented. The studied precast concrete connection is a typical connection currently used in Brazil practice for simple joints.

The column had 1400 mm of height and rectangular cross section with 500 mm $\times$ 400 mm. The corbels had 400 mm $\times$ 400 mm $\times$ 250 mm and were precast with the column. The beams had 1900 mm of length and were comprised by a precast part with 400 mm of height and a cast-in-place part with 270 mm of height. The compressive strength of the concrete used in the production of precast parts was 40 MPa while the cast-in-place had 25 MPa. The continuity bars were comprised by two 16 mm bars passing through the column and four 8 mm bars on each side of the column; the total steel area was 804 mm^2. To prevent the cracking, a steel mesh with 4.5 mm wires was used in the concrete cover of the slab. Fig. 1 shows the dimensions of the model and further details of the continuity reinforcement. Transverse reinforcement comprised by six 8 mm bars was used in both sides of the column. This procedure is already known, due to it was mentioned in COST-C1 [19], and it was used to obtain a cracking control in the connection and to provide integration between the bars of the continuity reinforcement.

Strain gages were used for measuring the strains in negative reinforcement, which is the one that prevents the negative bending moment, inclinometers to measure the beam rotations, transducers to measure the vertical displacements and hydraulic jacks for applying the load (Fig. 2).

To determine the rotation of the connection, transducers and inclinometers were used and both provide similar results. The use of inclinometers is innovative for this purpose and it is recommended for future research. Under the point of loading application, transducers measured the vertical displacement of the beams. The static monotonic test was performed under force control. Electrical resistance strain gauges were used to measure the local strains in the continuity reinforcement during loading. Fig. 3 illustrates the instrumentation and the test setup.

In the test setup were used three reaction frames, each one with a hydraulic jack. Two of them were used to apply the monotonic load in the end of the beams and the third hydraulic jack was placed on the top of the column to apply a constant load during the test. This procedure was adopted in order to simulate the loading come from up floors and also to stabilize the model. In the test, a vertical loading was applied in the end of the beams producing negative bending moment on both sides of the column. The distance from the point of load application to the center of the connection rotation was 1.70 m. Three units of electrical resistance strain gauge load cells, one at each beam and another one on the top of the column, were used to determine the applied load from the hydraulic jacks.

3. 3-D finite element model

The numerical analysis proposed in this paper is focused on verifying that the numerical modeling is a potential tool to satisfactorily replicate the experimental connection behavior. The numerical simulation is an inexpensive alternative to structural analysis due to it replaces the physical models, which are expensive and time-consuming to be built. To validate the simulation results the numerical data was compared with the experimental results.

3.1. Geometry

A three-dimensional nonlinear finite element model was created for replicating the slab-beam-column connection of the