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Analytical modeling of post-tensioned precast beam-to-column connections

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ABSTRACT

In this study, post-tensioned precast beam-to-column connections are tested experimentally at different stress levels, and are modelled analytically using 3D nonlinear finite element modelling method. ANSYS finite element software is used for this purposes. Nonlinear static analysis is used to determine the connection strength, behavior and stiffness when subjected to cyclic inelastic loads simulating ground excitation during an earthquake. The results obtained from the analytical studies are compared with the test results. In terms of stiffness, it was seen that the initial stiffness of the analytical models was lower than that of the tested specimens. As a result, modelling of these types of connection using 3D FEM can give crucial beforehand information, and overcome the disadvantages of time consuming workmanship and cost of experimental studies.

1. Introduction

Reinforced concrete (RC) is a widely used building material in the world, because it is reliable, cheap, easy to use and there are sufficient skilled workers to work with. A large number of experiments were made on RC members which has a heterogenous and unisotropic material properties. Although experimental methods give realistic results, they can cause problems in terms of volume, size, shape of RC members, loading and supporting conditions along with the material cost. Analytical modelling of RC members can also be done by using numerical methods. RC members generally show nonlinear behaviour. Therefore, nonlinear analysis is preferred method on these members for a realistic simulation of the applied load step by step. A continuous analysis is made at each step by using the results from preceding step. Moreover, distribution of stress and crack can be determined with the analysis of RC members. The accuracy of a model obtained with analytical modelling depends on the accuracy of material assumptions, a realistic model and support conditions [1].

When the literature was examined, it was seen that there has been a lack of analytical studies on the stress rates applied to prestressed strands which provide the post-tensioned connection between the beam and the column. A summary of the studies encountered at the literature are presented below.

Willam and Tanabe [2] carried out a finite element analysis of reinforced concrete structures concerning seismic behavior of structures, cyclic loading of reinforced concrete columns, shear failure of reinforced concrete beams, and concrete steel bond models. Shing and Tanabe [3] studied the inelastic behavior of reinforced concrete structures under seismic loads. This study contains applications of the finite element method of reinforced concrete columns, the analysis of reinforced concrete components in bridge seismic design, and the modelling of the shear behavior of reinforced concrete bridge structures. Fanning [4] modelled two beams equipped with discrete reinforcements, one being reinforced concrete and the other prestressed concrete. Fanning used the Solid65 element for the concrete. To define the prestressed beam, the prestressing strands were equipped with an initial strain. The studies by Arnesen et al. [5], dealt with the issue of plane stress using the theory of plasticity. In their study, a two-dimensional plane member with four joints was used in the modelling of concrete. The behavior of the concrete was modelled as linear elastic until the elasticity proportion limit determined through the von-Mises elliptic was reached and later modelled as linear hardening plastic. Barbosa and Riberio [6] created two different models for the beam in their research. First model is made by using Solid65 elements, and second use a special version of the same element at which the reinforcements are modeled with volumetric proportions.

The best solutions in Barbosa and Riberio's study were obtained from the model in which hidden reinforcement was used. Faherty [7] analyzed reinforced concrete and prestressed concrete beams through a finite element method. In this study, the linear behavior of reinforced concrete and prestressed concrete beams, anchorage slip, bilinear steel properties, and crack progress in concrete were examined. The results obtained from the prestressed concrete beams were similar to those in the experiment performed by Branson et al. [8]. Kachlakev [9] studied beams externally strengthened with reinforced plastic carbon fiber (CFRC) with no stirrups being used in the experiment. Wolanski [10] modelled reinforced

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concrete and prestressed concrete beams. During the first step of this study, reinforced concrete model was tested and the fracture loads of bending, and shearing reinforcement on the beam were determined through the model. The results obtained from the reinforced concrete model were applied to the prestressed beam. Özcan et al. [11] carried out experimental and finite element analysis of three steel fibre reinforced concrete (SFRC) beams. The beams were loaded until the tensile steel bars broke into two pieces. The SFRC beams modelled using nonlinear material properties adopted from an experimental study were analyzed by ANSYS until the ultimate failure cracks. Ellobody et al. [12] studied on the behavior and design of axially loaded concrete-filled steel tube circular stub columns. The external diameter of the steel tube-to-plate thickness ranged from 15 to 80 mm covering the compact steel tube sections. The results obtained from the finite element analysis were verified against experimental results. Pham et al. [13] studied the bond characteristic between CFRP and concrete. The behavior of 12 shear-lap specimens was modelled using a combination of smeared and discrete cracks. The Rankine's and nonlinear fracture mechanics, where both modes I and II fractures are accounted, failure criteria were used for the smeared and discrete cracks, respectively. The smeared crack model is based on Rankine's failure criterion, whereas the discrete crack model is based on nonlinear fracture mechanics. Ellobody and Young [14] used an accurate nonlinear finite element model to analyse the behavior and design of axially loaded concrete-filled square hollow section (SHS) and rectangular hollow section (RHS) steel tube columns. The nonlinear material models for confined concrete and steel tubes were carefully modelled in the finite element analysis.

The optimal rate of stress cannot be determined for precast structures in which beam-to-column connection provided by post-tensioning causes:

- Economic losses for countries that supply most of the material used in precast from other countries.
- Failure of the structure by the rupture of the prestressed strands during fabrication or after construction even in a light earthquake caused much stressing of these strands.
- In case of holding down stress rate, it causes increase in the number of worker, time and material loss due to they could not be derived benefit from prestressed strands at a required level.

In this study, one cast-in-place and three precast beam-to-column connections, previously experimental tested by Kaya [15], were modelled analytically by using the 3D nonlinear finite element method. In the modelling of the cast-in-place and precast specimens, the ANSYS program was used [16–18]. Prestressing strands of the precast specimens were stressed to 40% (CP1), 50% (AP1) and 60% (DP1) of their ultimate strengths. Therefore, prestressing level of 15.24 mm strands were used as an variable in this study. A prestressing force is applied to the columns of all members at 10% of the axial load capacity of these members in the first step of loading program. Post-tensioning is applied to the prestressed strands which provide connection between the precast column and beam. Cyclic loads, such as earthquake effects, are applied in a horizontal direction from the beam ends of all members in the last step. The results obtained from analytical studies are compared to those from experimental studies in terms of strength, behavior and stiffness.

2. Experimental study

2.1. Test setup

The model used in the study was formed by extracting the parts remaining between the moment zero points of the external joint in order to represent the frame behavior [15]. The test specimens were connected on a table installed on the slab where the columns were placed horizontally and the beams were placed vertically. In this way, specimen with an well known behaviour and geometry was formed [19]. The sizes of the test specimens were designed to be greater than 1/3 of the sizes applied in practice in accordance with the ACI T1.1-01 specification [20]. A two story building was designed and analyzed according to the seismic zone 1 of the Turkish Earthquake code [21]. Beam and column connection with its components should be highly ductile. In the cast-in-place test specimen, the beam reinforcement steel ratio was 0.0053 at the top and bottom of the beam. Cyclic loads similar to earthquake loads were applied to the specimens in horizontal direction. To increase the flexural capacities of the cast-in-place and precast specimens of the columns, a 320 kN prestressing load was applied using four prestressed strands, each with a diameter of 12.70 mm.

The cross-sections of the columns were 300×300 mm and the cross-sections of the beams were 240×350 mm. In addition, there were surface concretes at 40 mm width at the beams. In the columns of all the specimens, four ∅16 longitudinal mild steel and ∅8 stirrups with 100 mm spacing were used. The top and bottom of the beam of the cast-in-place specimen, four ∅12 longitudinal reinforcement and ∅8 stirrups were used at 100 mm spacing (Fig. 1). Four ∅12 longitudinal reinforcement with total 18 stirrups with two different types were used for precast beams [15]. The columns of the precast specimens differed from the column of the cast-in-place specimen in terms of the reinforcement of the corbels (Fig. 2). At the corbels of these specimens, there were four ∅12 flexural reinforcements, three ∅8 vertical and three ∅8 horizontal stirrups [15]. There are ducts through which the prestressed strands pass into precast column and beams, and plastic pipes at which the grout was poured into the ducts and the spaces between the columns and beams (Fig. 2).

2.2. Materials

The test specimens were produced using prestressed strands and mild steel, the properties of the prestressed strands and the properties of the reinforcement bars are presented in Tables 1 and 2, respectively.

The concrete that was used for casting the specimen are called as base concrete afterwards in the text. The base concrete of specimen was C50. The water–cement (W/C) ratio of the base concrete was 0.38 and an additive (Sikament 300 produced by SIKA) was used. The additive was used in a 6% ratio to the cement weight in the cement slurry which was injected into the ducts through which the prestressed strands passed in the precast members. The W/C ratio was 0.37 in the cement slurry. Finally, the surface concrete of all the cast-in-place and precast test specimens were prepared. To fill space between column and beams for precast members, grout which has a non-shrinking property (EMECO S53 was produced by YKS). The dry mix of EMECO S53 was mixed with water and the W/C ratio of the grout was 0.35. In order to determine the strengths of the base concrete; concrete samples were taken from the base concrete of the cast-in-place and precast specimens. The compressive strength of the concrete samples of different sizes taken from the test specimens were translated into a cylinder compressive strength of 150×300 mm [22] and the strengths of the concrete samples are presented in Table 3.

After the precast beams were installed over the columns, the spaces between the columns and beams were filled with grout. When the grout was able to provide the strength required (Table 3), the post-tension loading was applied began. This operation was carried out as explained below. Using the modulus of elasticity and tensile strength values of the prestressed strands of 15.24 mm