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The effect of short cantilever beam formation on the structural behavior of precast post-tensioned connections

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ABSTRACT

This study is performed in order to determine the effect of the short cantilever beam formation under beam element in precast post-tensioned connections to the structural capacity of the system. With this purpose, four specimens are designed for the tests. One of them (SCP0) is without short cantilever beam and the three others (SCP1, SCP2 and SCP3) are formed with short cantilever beam in different dimensions. The investigation is made in both experimental and numerical framework. In the experimental part of this study, displacement controlled analysis is done and hysteresis loops of specimens are obtained between 0% and 4% story drift values. In the numerical part, these four specimens are modelled in SAP2000V.14 and nonlinear static analysis is used to obtain the load-story drift curves. The structural capacities are observed in terms of connection stiffness and ductility. The results obtained from numerical studies are compared with the experimental ones. Closer results are achieved in both frameworks. As a result, the contribution of short cantilever beam to the structural capacity of the system is clearly seen and proposed as efficient solution for higher ductility demands.

1. Introduction

Precast concrete frames have been in use with an increasing demand and interest as high quality structural systems. Effective controlling conditions of structural members, the speed of construction and the low relative cost of such frames are the main sources of the preference for the designers. It should be emphasized that the performance of this structure type is determined by capacity and ductility level of the connections. In response to these needs, conveniently designed beam to column connection have to transfer forces adequately between precast elements so that the overall building structure behaves monolithically. For precast connections, shear transmission mechanism in connections is provided by the clamping force of post-tensioning. The post-tensioning tendons and mild steel rebars at the top and bottom of the cross section fulfill the moment capacity of the connection. Besides, mild steel rebars improve the energy dissipation properties of beam to column connections [1–3]. In this manner, there is no requirement to design short cantilever beam, however, when prestress loss of post-tensioning tendons have to be prevented, such as prestressing force loss derived from beam elongations obtained in higher modes of multi-story structures, short cantilever beam design should be used due to its contribution to shear transmission mechanism. Furthermore, this design is also proposed in order to circumvent the stiffness losses arising from the opening of the interface of the beam to column connection [1,4].

Considerable research has been performed on precast concrete connections in the past three decades owing to the advantages mentioned. The two large scale studies have been in the foreground among the others. First one is a multi-year multi-phase program initiated by NIST (National Institute of Standards and Technology) in 1987 [5–7]. This research is conducted for the development of a rational design procedure in seismically active regions. Second one is Precast Seismic Structural Systems research, US-PRESSS program with the aim of developing design guidelines for precast/prestressed concrete seismic systems in 1989 [8,9].

The NIST program is divided into four phases, and includes monolithic connections for control purposes. According to the results of NIST Phase-I test program, a post-tensioned precast concrete beam–column connection is shown as ductile connection for high seismic regions. However, the energy dissipation characteristics of the precast concrete connections should be improved [5–7]. To improve energy dissipation characteristics, in Phase-II of the NIST study [5–7], the post tensioning force is moved closer to the beam centroid. It is also reported that the energy dissipation is increased using prestressing strands instead of post-tensioning ones. But, as a result of Phase-II, it has been shown that the stiffness of the connections is excessively degraded in large

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deformations of hysteresis loops. For this problem, in Phase-III, the partially debonded tendons are chosen. The concept of partially bonded length becomes an important key of the problem of zero slope hysteresis loops and consequently zero stiffness. After these first three phases, Phase-IV points out that the moment capacity is greatly improved using bonded mild steel reinforcement at the top and bottom of the cross-section with the unbonded prestressing tendons [5–7].

US-PRESSS research program is intended to build precast structures resistant to seismic activity. The hybrid post tension, pretension, tension and compression yield connections have been experimented under pseudo-dynamic tests and the damage levels are observed. The structural behavior principles concluded from NIST program are taken into account in the examples of US-PRESSS program. It has shown that all these connection types are substantially suitable for any earthquake precast design [8,9].

With the same approaches of two detailed main studies, hybrid precast connections are tested in METU by Pınarbasi [10]. The study concludes that partially bonded post-tensioning reinforcement contributes significantly to flexural capacity and the energy dissipation characteristics can be increased by using non-prestressed reinforcement at the top and bottom levels of the cross-sections [10].

In study of Ertas [4], different precast connection types are tested and their performance parameters are examined under seismic activities. After this level, hybrid precast post-tensioned connections are added to the test program and the contribution of mild steel percentage to flexural moment capacity is investigated. It is observed that the mild steel percentage should be in the range of 20–30% for best connection ductility performance. It is also highlighted that the hysteretic behavior of hybrid connections approaches to that of the monolithic subassembly with increasing mild steel ratio. Similar to the study of Ertas, Ozden and Ertas have investigated how the mild steel ratio affects the structural behavior of post tensioned precast connections and it showed that the same range 20–30% should be used for adequate performance. It has added that opening of the interface of hybrid connection changes significantly to the secant stiffness and therefore displacement based methodology is more reasonable in seismic design of these post-tensioned precast hybrid connections [11]. The study of Atalay proposed that the hybrid connection detail containing steel corbel along with post-tensioning bolt and mild steel has superior performance in terms of moment capacity, stiffness, energy dissipation and residual displacement values. It has also pointed out that the stiffness losses of cross-sections arise from the opening of the interface of the beam to column connection [1].

At this point, short cantilever beam design increases the initial stiffness of the cross- sections and the stiffness decrease resulted from the opening of the interface can be removed. Additionally, short cantilever formation under beam element enhances flexural moment capacity in shear transmission mechanism and hold stiffness loss minimal up to large deformations. On the other hand, if yielding of post-tensioning bars occurs, shear friction force can not be transferred in connection. It is an undesirable possibility in structural response of beam to column interface. In this case, short cantilever formation provides this transmission mechanism and the section is not influenced by yielding of post-tensioning bars. Furthermore, by using short cantilever, considerable prestress losses of post-tensioned connections, particularly in multi-story structures, may be efficiently prevented.

Within this frame, to demonstrate the contribution of short cantilever formation under beam element on structural behavior of connection, an experimental study is performed with four specimens in different short cantilever dimensions and gains to shear transmission mechanism have been shown clearly. To support this experimental work, the experimental results are compared with the numerical ones.

2. Theoretical background

The design and analysis steps of post-tensioned connections have been significantly different mainly due to their structural behaviors compared to the monolithic samples. Most of the deformations of the frame occur due to the opening and closing of the connection at the interface between precast beam and column. In this case, the strain values of partially mild steel and bonded post-tensioning bar are substantially important in determining capacities of samples.

In design of hybrid connections [12,13], the calculation of flexural strength relies on rotation at the interface at ultimate strength of the mild steel. The elongation of mild steel reinforcement (Δ_{ms}) can be obtained from the following equation:

$$\Delta_{ms} = (l_{un} + \alpha_b d_b) \cdot \varepsilon_{su} \quad (2.1)$$

In Eq. (2.1), "l_{un}" represents unbonded length of mild steel while "α_b" is debonding length coefficient. "d_b" is bar diameter and "ε_{su}" is 90% of the ultimate strain. The elongation of prestressing tendons (Δ_{pt}) can be easily calculated by using similar triangles from Eq. (2.2) as seen in Fig. 1. In Eq. (2.2), "h" is height of the beam and "d" is effective depth of the beam. "c" represents height of the compression block.

$$\Delta_{pt} = \Delta_{ms} \cdot \frac{\left(\frac{h}{2} - c\right)}{(d - c)} \quad (2.2)$$

The total strain in prestressing tendon "ε_{pt}" due to the rotation of the connection and the initial prestressing is obtained from Eq. (2.3). In Eq. (2.3), "ε_{pi}" is the initial strain of the tendon. "L_{un}" represents unbonded length of the tendon.

$$\varepsilon_{pt} = \varepsilon_{pi} + \frac{(\Delta_{pt})}{(L_{un})} \quad (2.3)$$

Within this frame, the flexural moment capacity of beam–column connection is obtained by summing the contribution of mild steel "M_{ms}" and prestressing tendon "M_{pt}".

$$M_{ms} = A_s \cdot f_u \cdot \left(d - \frac{\beta 1 \cdot c}{2}\right) - A'_s \cdot 1.25 \cdot f_y \cdot \left(d' - \frac{\beta 1 \cdot c}{2}\right) \quad (2.4)$$

$$M_{pt} = A_{pt} \cdot f_{pt} \cdot \left(\frac{h}{2} - \frac{\beta 1 \cdot c}{2}\right) \quad (2.5)$$

In the Eqs. (2.4) and (2.5), "A_s" is mild steel area in tension side and "A'_s" is mild steel area in compression side. While "f_u" is ultimate strength of mild steel, "f_y" and "f_{pt}" are yield strength of mild steel and stress on tendon respectively. "A_{pt}" represents the area of tendon. "β_1" is coefficient of rectangular compression block for ACI 318 [14] and "d'" is cover thickness. In calculating the flexural capacity of the system, the effective depth of compression block is determined by force equilibrium as seen from Fig. 1 by adding up short cantilever beam formation to the system, the flexural capacity is increased by tension bar area. Tension bar area "A_{st}" can be calculated according to the following equation:

$$A_{st} = [\{V_d \cdot a_v + H_d.(h - d)\}/0.8 \cdot f_{yd} \cdot d] + [H_d/f_{yd}] \quad (2.6)$$

In the Eq. (2.6), "V_d" and "H_d" represents shear and lateral load on short cantilever beam, respectively. "f_{yd}" is design yield strength of steel [15]. With these tension bars used and decrease in rotation of connection, it is surely demonstrated that this formation under main beam element enhances structural capacity and ductility.