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Flexural strength and stiffness of block-out connections for steel columns

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ABSTRACT

In many steel buildings, the columns are attached to the foundation through a block-out in the slab-on-grade that is later filled with unreinforced concrete. Engineers typically neglect the block-out concrete in design, effectively treating block-out connections as exposed connections with pinned behavior. Quantifying the flexural strength and stiffness of block-out connections is helpful for determining moment demands on foundations and may lead to more economical connections at the base of steel moment frames. Eight experimental specimens (two-thirds scale) were subjected to lateral loads to investigate the effects of column size, block-out thickness, and load orientation on connection flexural strength and stiffness. The observed flexural strengths were 1.4–2.7 times greater than those calculated neglecting the block-out concrete, because the block-out concrete effectively thickened and expanded the column base plate. A simple method was developed that predicted the flexural strength of the block-out connections to within 10 percent. The effective flexural stiffness at the base of the columns that were tested could be reasonably estimated using a model that combines the theory of beams on elastic foundations with a base rotational spring.

1. Introduction

Columns in steel buildings can be attached to the foundation in a variety of ways. Three general types of column-to-foundation connections in steel buildings are: exposed, embedded, and block-out connections. Exposed connections, Fig. 1(a), are used when the top-of-footing is at the same elevation as the top-of-slab or when steel columns are attached to concrete pedestals. Embedded connections, Fig. 1(b), are intended to resist large moments and shears and may be used at the base of steel moment frames. Block-out connections, Fig. 1(c), are used in many commercial and residential steel buildings so that the slab-on-grade can be poured prior to the installation of any structural steel (minimizing/eliminating the overlap of concrete and steel trades on the job site) and so the anchor bolts do not interfere with the finished floor. This paper explores the performance of block-out connections at the base of gravity columns [Fig. 1(c)].

Block-out connections are generally treated as exposed connections by engineers. Most of the research that has been conducted on steel column-to-foundation connections has focused on exposed connections [Fig. 1(a)]. A design guide based on these studies [1], is the basis for most column base connection designs. In block-out connections, the column is connected directly to the footing through a block-out in the slab-on-grade [Fig. 1(c)]. Later, the block-out is filled with unreinforced concrete or grout. The depth of the block-out is usually 0.3–0.6 m (1–2 ft), with the deeper block-outs used when the footings are lower to accommodate drain pipe bends or frost lines. Even when deep block-outs are used, engineers usually neglect the presence of the block-out concrete in design calculations, treating the connection as an exposed connection [Fig. 1(a)].

The flexural strength and stiffness at the base of gravity columns with block-out connections is usually neglected, but could result in undesirable foundation failures during earthquakes. Since 2001, erection safety guidelines have required four anchor bolts and nominal lateral resistance for all columns [Fig. 1(c)], so all column connections are designed to transfer some bending moment. Still, gravity column connections are typically considered pinned connections for analysis purposes, partly because the soil underneath spread footings is not stiff enough to prevent rotation and assuming zero flexural stiffness seems conservative. While this assumption may be appropriate for some aspects of building design, it implies that steel gravity columns cannot impart moments into the footings and surrounding soil. The literature and the results presented in this paper demonstrate that gravity columns, particularly those with block-out connections, can impart large moments into the footings and surrounding soil during earthquake loading, resulting in undesirable failure modes. Assuming pinned behavior for connections like Fig. 1(c) is conservative for the design of columns and superstructures, but it is not conservative for foundation design [2].

Another motivation for exploring the strength and stiffness of block-out connections is the possibility of more economical base connections

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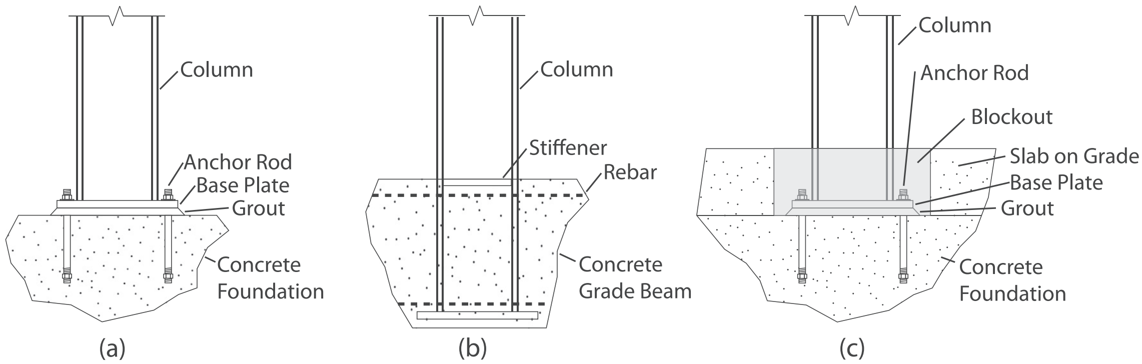

Fig. 1. Column-to-foundation connections: (a) exposed; (b) embedded; (c) block-out (shallow embedded).

for moment resisting frames. Currently, deeply embedded connections [Fig. 1(b)] are used at the base of many moment resisting frames. Such connections require coordination between the concrete and steel trades adding expense and time to a project. Columns surrounded by unreinforced block-out concrete are faster and less expensive to construct.

2. Previous research

A number of studies have investigated the flexural strength and stiffness of column baseplate connections without the presence of block-out concrete. DeWolf and Bicker [3] review base plate design procedures from the 1950s through the 1980s, including studies that compare design strengths (axial and flexural) with experimental results. Hensman and Nethercot [2] review column baseplate experimental studies and models published prior to 1999, with an emphasis on flexural stiffness. The current design guide for baseplates published by AISC [1] provides recommendations for determining the flexural strength of baseplate connections, with limited discussion of flexural stiffness. The flexural strength model in Fisher and Kloiber [1] assumes an end-bearing mechanism with a stress distribution at the ultimate state as shown in Fig. 2(a). More recent experimental work [4] has confirmed that this distribution [Fig. 2(a)] is reasonable for exposed base plates, particularly for wide flange shapes with four baseplate anchor rods.

Other work has addressed embedded steel shapes without significant end-bearing, that have flexural strength from a side-bearing mechanism. Marcakis and Mitchell [5] tested 25 specimens involving steel corbels embedded into concrete columns. They used their experimental results to improve a connection strength model where shear and bending moment are resisted by compression stress blocks [Fig. 2(b)]. The strength equation proposed by Marcakis and Mitchell [5] corresponded reasonably with their experiments when an effective

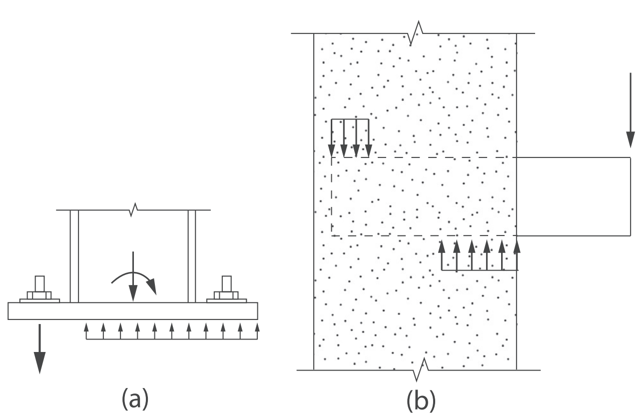

Fig. 2. Mechanisms for flexural strength: (a) end-bearing mechanism; (b) side-bearing mechanism.

flange width was used, and is the equation that engineers typically use to compute the connection strength for steel shapes embedded in concrete [Eq. 6.9.1 of the PCI Design Manual [6]].

In contrast to the studies that have been mentioned, columns with block-out connections [Fig. 1(c)] may have significant flexural strength from *both* end-bearing and side-bearing mechanisms. Such connections are termed "shallowly embedded" because the embedment is small enough that the end-bearing mechanism still contributes meaningfully, perhaps dominating, the flexural strength and stiffness. The closest experiments to column block-out connections in the literature are those reported by Cui and Nakashima [7]. They reported results from tests of eight specimens consisting of square HSS [200 mm × 200 mm (7.9 in. × 7.9 in.)] columns embedded varying distances [0 mm, 100 mm (3.9 in.), 200 mm (7.9 in.)] into concrete with varying reinforcement. Columns were loaded with an axial force corresponding to roughly 0.2 times the axial yield capacity, and then loaded laterally. The experiments showed that specimens with 200 mm (7.9 in.) of embedment had twice the lateral strength and 1.5 times the lateral stiffness of the exposed connection (0 mm embedment). These results provided some of the motivation for the present study, by demonstrating remarkable added strength and stiffness from modest amounts of embedment.

Other experiments on shallow embedded connections, in different contexts, have also indicated unexplained strength and stiffness. For example, some pile-to-cap connections are intentionally designed not to transmit moments, but actually do. Xiao et al. [8] tested "pinned" HP pile-to-cap connections and found surprising strength and stiffness considering only 127 mm (5 in.) of embedment of the steel pile into the pile-cap. The strength was much greater than that predicted by Eq. 6.9.1 of the PCI Design Manual [6]. Richards et al. [9] also noted unexplained strength and stiffness in pipe pile-to-cap connections with shallow embedment of 0.5 times the pipe diameter and no reinforcement. Follow-on tests showed that a 305 mm (12 in.) diameter steel pipe, with 102 mm (4 in.) of embedment and no reinforcement, had half the connection flexural stiffness of a pipe with 457 mm (18 in.) of embedment [10].

Other studies on column-to-foundation connections are pertinent to the present work. Grilli et al. [11,12] investigated the strength and stiffness of deeply embedded column-to-grade-beam connections. The connections they investigated relied primarily on a side-bearing mechanism [similar to Fig. 2(b)], but also had contributions from a bearing plate mechanism (bearing plates were welded to the columns at the top-of-slab elevation). Grilli et al. [11] tested three specimens that were the same except for axial load effects: one with no axial force, one with axial compression corresponding to about 20% of the design axial yield force (445 kN), and one with axial tension of the same magnitude. The axial compression increased flexural strength and stiffness of the connection by 10%. The axial tension had minimal impact on strength, but increased stiffness by 6%. Rodas et al. [13] developed a model for the rotational stiffness of embedded connections but did not include the