Recent Research on Column Base Connections

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Extensive testing is helping quantify the conservatism in current design approaches.

COLUMN BASE CONNECTIONS are used in virtually all types of steel structures. Arguably, they are the most important type of structural connections, transferring forces from the entire structure into the foundation. Unfortunately, in comparison to other structural connections, such as beam-column connections, they have received relatively limited attention in research. However, recent work by the authors has resulted in a wealth of experimental data that sheds new light on various aspects of the response of these connections. Supported by AISC and the National Science Foundation, this research is wide ranging and encompasses 20 large-scale experiments featuring exposed column base plates. The findings from these experiments have important implications for several aspects of base connection design—primarily, design methods outlined in the AISC *Steel Design Guide No. 1, Base Plate ad Anchor Rod Design*.

The tests described in this article may be subdivided into three series, each addressing one aspect of base connection design. The first series consists of seven large-scale tests investigating the moment capacity of base connections under compressive axial load. A second series of seven tests focuses on various shear transfer mechanisms, and a third series of six tests examines the effect of weld details on connection performance.

Flexural Strength of Column Base Connections

Figure 1 schematically illustrates a typical exposed column base connection, with its various components. *Design Guide 1* provides methods for characterizing the strength of exposed column base connections under combinations of axial force and flexure. These methods are based on the assumption that the applied forces will be resisted through the development of a triangular or a rectangular stress block under the bearing (compression) side of the connection, and the development of tensile forces in the anchor rods as also indicated on Figure 1. Under this situation, the strength of the connection may be controlled by the flexural yielding of the base plate on the compression or tension side, or by anchor rod yielding.

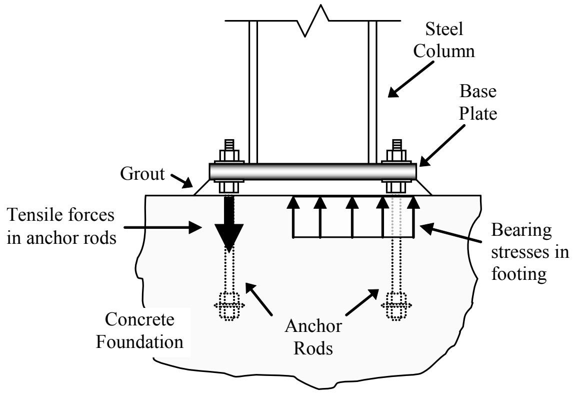

Fig. 1: Schematic illustration of connection and force transfer.

The seven experiments conducted within Series 1 of the testing program were designed specifically to examine the degree to which these methods accurately represent the strength of the connection. The key variables investigated within these seven experiments included the base plate thickness, anchor rod strength and layout and the magnitude of axial force. Figure 2a shows the test setup that was designed to apply combinations of these loads, while Figure 2b shows a close-up of one of the test specimens during the testing. Figure 2c shows the corresponding load-deformation curve.

While the tests yielded large volumes of data, two important observations have profound implications for the design of column base plate connections.

First, all specimens showed excellent deformation capacity, exhibiting rotations corresponding to column drifts of 7%–10%, without significant strength degradation. This response may be considered extraordinary, especially when compared to qualification standards for beam-column connections, such as outlined in the AISC *Seismic Provisions*, which require the beam-column connections to maintain strength until rotations of 4%. Moreover, despite the pinched hysteretic response, due to contact and gapping between the base plate and the grout foundation, significant energy dissipation was observed in all specimens. This suggests that the practice of designing the base plate to remain elastic during seismic events may be conservative, because significant deformation and energy dissipation capacity is available in the base plate as well.

Second, an analysis of connection strength carried out per the method provided in *Design Guide 1* resulted in perhaps the most important finding of the test program: The experimentally observed strength, on average, is 80% greater than the estimated strength. This indicates a high degree of conservatism in the current design approach.

A closer inspection of the test data indicates that for specimens where flexural yielding of the base plate on the compression side was the controlling limit state, the experimentally observed strength of the connections is more than

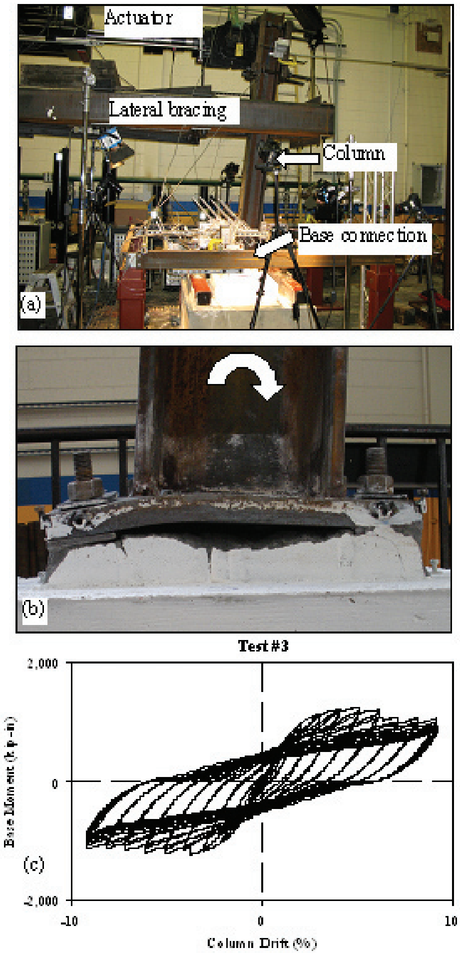

Fig. 2: Flexural response of base connections showing (a) test assembly, (b) close-up of grout damage and plate bending, and (c) hysteretic load deformation plot.

twice that implied by the current approach. On the other hand, when anchor rod failure controlled the strength, the experiments and analysis were in good agreement.

A detailed examination of test data, complemented by visual observations of response, indicates that the ultimate strength of the connection is controlled by the formation of a plastic mechanism, rather than yielding of a single component, as shown in Figure 2c. Thus, even after flexural yielding is reached on the compression side, the connection continues to gain strength until the anchor rods fail or the base plate on the compression side yields in flexure. Consideration of this mechanism-based strength will significantly reduce the conservatism in current design approaches, by a factor of nearly two in some cases.

Shear Transfer in Base Connections

Shear transfer in base connections is critical in both moment and braced frames. In moment frames, the shear is often transferred through friction developed in the bearing portion of the connection. However, when such a bearing zone is not present (e.g., in braced frames or in moment frames where the columns have tensile axial loads), shear transfer mechanisms must be carefully considered and designed. Seven tests were conducted to characterize shear transfer in base connections, using an innovative testing apparatus that enabled the application of shear forces in the presence of both tensile and compressive axial loads (see Figure 3).

Three popular shear transfer mechanisms were examined in detail, including surface friction, anchor rods, and the bearing of a shear lug embedded in the footing. Surface friction typically will resist some of the shear, unless there is net tension in the column, whereas shear transfer through anchor rods or the shear lug must be considered if there is tension or if friction, by itself, is not sufficient to resist the applied shear.

Three experiments investigated surface friction, with the application of cyclic shear displacements under compressive axial load. To reflect typical construction practice, two of these tests included shim stacks under the base plate. The third test did not include shim stacks, to investigate friction between steel and grout. Based on the tests, a coefficient of friction value of 0.45 is recommended for use in design, which is slightly higher than the 0.40 value suggested by *Design Guide 1*.

Two tests investigated the shear resistance of anchor rods under a combination of imposed axial tensile loads and cyclic shear/flexural loading. The connection detail included welded plate washers to minimize slip and ensure equitable force distribution among all anchor rods. The tests indicated that the current approach suggested by the *Design Guide 1* is appropriate. In this approach, the anchor rods are assumed to bend in reverse curvature over a distance between the top of the grout pad and the

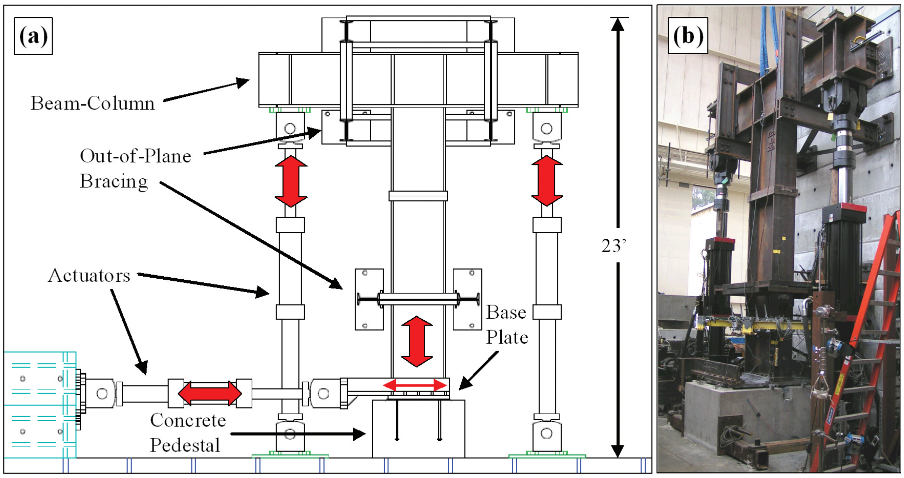

Fig. 3: Schematic and photograph of test setup for testing base connections under direct shear and axial loads.

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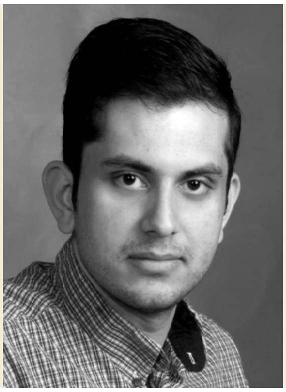

center of the welded plate washer. Thus, the effective length is equal to the thickness of the base plate plus half the thickness of the plate washer. Once this length is established, tensile stresses due to flexure and axial load may be combined with shear stresses through a stress-interaction equation to determine the shear force capacity.

Two tests featured a pocket in the concrete footing into which a shear key was inserted to investigate the failure modes and capacities associated with a shear key bearing mechanism. These tests revealed that the "45° cone method" currently recommended by *Design Guide 1* is not conservative for large concrete foundations due to the size-effect in concrete, where failure is controlled by fracture initiation. In these situations, an alternate method, described as Concrete Capacity Design (CCD) method, is recommended as the appropriate one.

Effect of Weld Details

Six two-thirds scale tests also were conducted to examine the effect of weld details between the columns and the base plates. Two weld details were considered. One featured Complete Joint Penetration (CJP) groove welds between the column flange and the base plate, whereas the other featured a Partial Joint Penetration (PJP) groove weld with a reinforcing fillet weld. These tests indicated that the CJP and PJP column base weld details, commonly used for design in high seismic regions, can sustain deformations corresponding to 3%-5% interstory drift that are sufficient for seismic design.

The PJP groove welded specimens performed at least as well as the CJP groove welds, because the reinforcement provided by the fillet welds minimized yielding in the weld root region. On the other hand, the access hole of the CJP groove weld resulted in a strain concentration near the heat affected zone, resulting in fracture earlier than in the PJP groove weld specimens. However, both these details were determined to show excellent performance.

Conclusions and the Path Ahead

Several recent studies funded by AISC have resulted in seminal knowledge about the response of column base connections. These have revealed significant conservatisms in current design approaches and also some areas of concern. The findings indicate an opportunity to make significant changes in the design of these important connections. Some changes may be in the actual design methods themselves, whereas others raise more philosophical questions from a system-design perspective. For example, the excellent deformation capacity observed for all test specimens is highly encouraging, because it suggests the possibility of permitting inelastic deformations in the base connections during an earthquake. Ongoing work by the authors aims to address some of these questions. It is anticipated that intensive collaboration with industry will accelerate this process. **MSC**

Both of the AISC documents referred to in this article are available online at ***www.aisc.org/epubs****.* Design Guide 1, *like all of the AISC design guides, is available as a free download for AISC members and for purchase by non-members. The AISC* Seismic Provisions *is available to all as a free download.*

This article is the basis of a presentation the authors will make at NASCC: The Steel Conference, May 11-14 in Pittsburgh. Learn more about The Steel Conference at ***www.aisc.org/nascc****.*