THE SEISMIC PERFORMANCE OF SHALLOWLY EMBEDDED AND DUCTILE BASE CONNECTIONS IN STEEL MOMENT FRAMES

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Abstract

Column base connections are used in steel moment frames to transfer loads from the superstructure into the supporting concrete foundation. Conventionally, these are categorized as exposed connections and embedded connections. Despite their importance, several aspects of their response warrant further study; this includes details prevalent in current practice (for which experimental data is missing) as well as prospective details designed for ductility. A series of seven large scale experiments are presented in this paper. Three specimens represent shallowly embedded base connections, known in practice as block-out connections wherein the base plate is overtopped by a slab-on-grade. Four other specimens represent dissipative/ductile exposed base connections with anchor rods specifically designed (as a below-ground fuse) to accommodate large inelastic base rotations accumulated over multiple seismic events. The test matrix interrogates the effect of column axial load and embedment depth, as well as that of anchor grade and size on response characteristics. The results provide encouragement for the use of dissipative base connections in steel moment frames, and provide new information regarding shallowly embedded base connections subjected to combinations of axial compression and flexure.

Keywords: Base connections; block-out; ductile; steel columns.

1. Introduction

Column base connections transfer gravity, wind, seismic loads from the entire structure into the foundation. Various approaches have been used to facilitate this force transfer, and particular details can have significant impacts on the overall strength and stiffness of each connection. Column base connections are broadly characterized as either exposed, embedded, or shallowly embedded (block-out) connections. Exposed base connections, shown in Fig.1a, are common in low-rise buildings where demands are moderate. Embedded base connections, shown in Fig.1b, are mostly used for mid- and high-rise buildings, when the moment and shear demands become exceedingly difficult to be transferred via exposed connections. This connection type requires extensive coordination between concrete and steel workers on site.

Shallowly embedded connection (also known as block-out connection), shown in Fig.1c, is the most preferable connection for contractors and architects, as it minimizes the overlap of concrete and steel workers on site. In this connection, the column is connected directly to the footing through a block-out (i.e. formed gap) in the overtopping slab (slab-on-grade), which is subsequently filled with grout or unreinforced concrete. Although recent experiments have examined the performance of shallowly embedded base connections, the effects of axial load have not been tested experimentally. This is one of the primary objectives of the proposed test program.

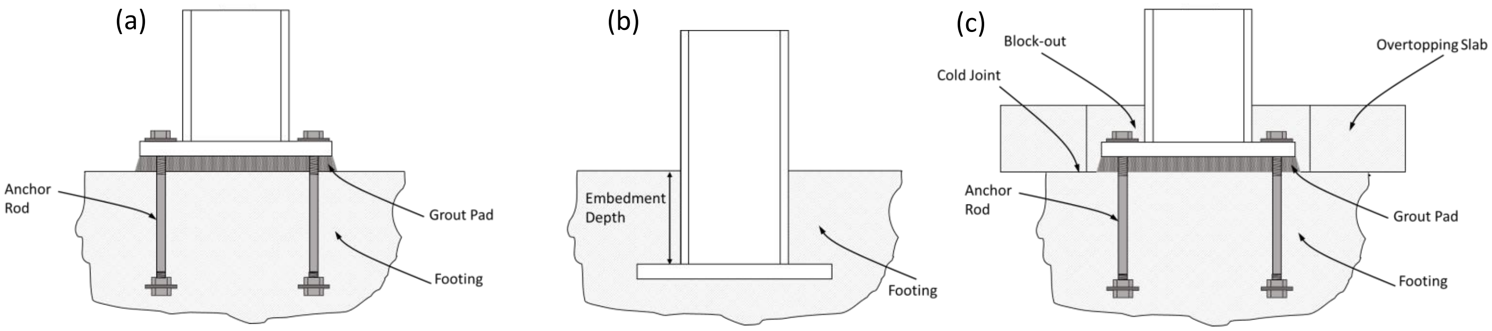

Fig. 1 – Common types of column base connections: (a) Exposed base plate connection, (b) Embedded column base connection, (c) Shallowly embedded base connection (Slab-overtopped)

An auxiliary part of this study investigates a separate (uncoupled) aspect—namely, the applicability of developing dissipative base connections. Column base connections are typically capacity-designed to be stronger than the adjoining column, presuming that the connection will be less ductile than the column. This is highly expensive. Research has shown that these connections are probably more ductile than the column, suggesting that this practice is not only expensive, but also counterproductive.

The current study examines the behavior of three shallowly embedded connections subjected to combined axial and flexure loadings, as well as four ductile exposed connections wherein the anchor rods are specifically detailed/designed to yield and accommodate large base rotations without large concentrated strains. The intent of this study is twofold: (1) to develop advanced understanding of the force transfer mechanism and effect of the added block-out on the strength and stiffness in the shallowly embedded connections, and (2) to evaluate the effectiveness of using anchor rod yielding rather than column plastic hinge formation at the base of steel moment frames through reliably ductile connections.

2. Background

A number of studies have investigated the flexural strength and stiffness of exposed base connections [1, 2, 3, 4, and 5]. The most current design guide for baseplate connection published by AISC (Design Guide One) [6] provides recommendations for determining the flexural strength of baseplate connections, with limited discussion of flexural stiffness and alternative configurations (e.g. embedded and block-out connections).

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The flexural strength model in Design Guide One [6] assumes an end-bearing mechanism employing a predetermined rectangular stress distribution on the bearing side, shown in Fig.2a.

Most previous work has explored steel to concrete connections with either end-bearing or side-bearing mechanisms. The few experiments on shallow embedded connections, in which both mechanisms engage, suggest significant strength and stiffness [7, 8]. However, there have been no prior experiments to quantify how block-out concrete contributes to the flexural strength and stiffness of base connections in moment frames subjected to axial compression and flexure. Motivated by this, the proposed tests will quantify the flexural strength and stiffness of block-out connections, filling a significant knowledge-gap.

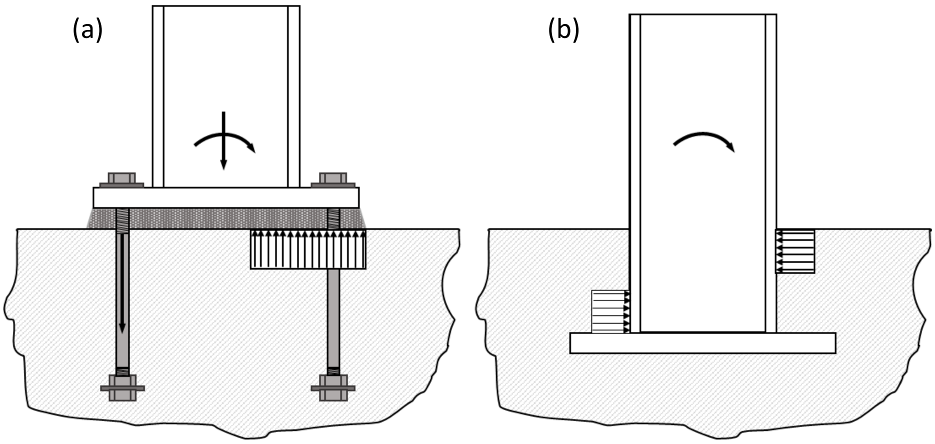

Fig. 2 – Flexural bearing mechanisms: (a) End-bearing mechanism, (b) Side-bearing mechanism

Apart from the connection configuration domain, structural design guidelines do not allow ductile/dissipative response in the base connections, requiring designers to design them as elastic and fixed, resulting in extremely expensive base connections. Recent experimental research [5] shows that the base connections may exhibit considerable ductility, whereas the columns have limited rotation capacity (due to local or lateral torsional buckling) [9]. Furthermore, building simulations [10] have evaluated the performance of steel moment frames with weak-base design, examining the interactions between these connections and the system to establish acceptance criteria for the components. The results show promise for supplemental research in this context. Motivated by this, the performance of steel moment frames with weak/dissipative base design is investigated experimentally to examine the relationships between base connection strength, deformation capacity, and structural performance.

3. Test Program

3.1 Specimen Description

Seven test specimens are designed and constructed in order to investigate the behavior of the two different connection types (shallowly embedded and ductile exposed connections) on various parameters; axial load and embedment depth, as well as anchor grade and size. The test matrix is provided in Table 1. The proposed tests have been refined to interrogate, with a modest number of experiments, various effects and behaviors of interest and allow effective comparison against previously conducted tests. Three tests (B-Series) represent shallowly embedded base connections, whose details is shown in Fig.3.

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Table 1 – Test Matrix

<table>
<tr><th>Test #</th><th>F1554 Anchor Grade</th><th>Anchor Diameter in [mm]</th><th>Anchor Reduced Diameter in [mm]</th><th>Column Embedment Depth in [mm]</th><th>Axial Load k [kN]</th></tr>
<tr><td>D1</td><td rowspan="2">55</td><td>0.75 [19]</td><td>0.5 [12.7]</td><td rowspan="4">-</td><td rowspan="3">50 (C) [223]</td></tr>
<tr><td>D2</td><td rowspan="6">1 [25]</td><td rowspan="3">0.75 [19]</td></tr>
<tr><td>D3</td><td rowspan="2">105</td></tr>
<tr><td>D4</td><td>-</td></tr>
<tr><td>B1</td><td rowspan="3">55</td><td rowspan="3">-</td><td rowspan="3">8 [203]</td><td>-</td></tr>
<tr><td>B2</td><td>50 (C) [223]</td></tr>
<tr><td>B3</td><td>100 (C) [445]</td></tr>
</table>

*All Tested with Column Section W14x370 (bf =16.5 [419])

*All Base plate dimensions (t_p x N x B) are 2 x 30 x 30 [51 x 762 x 762]

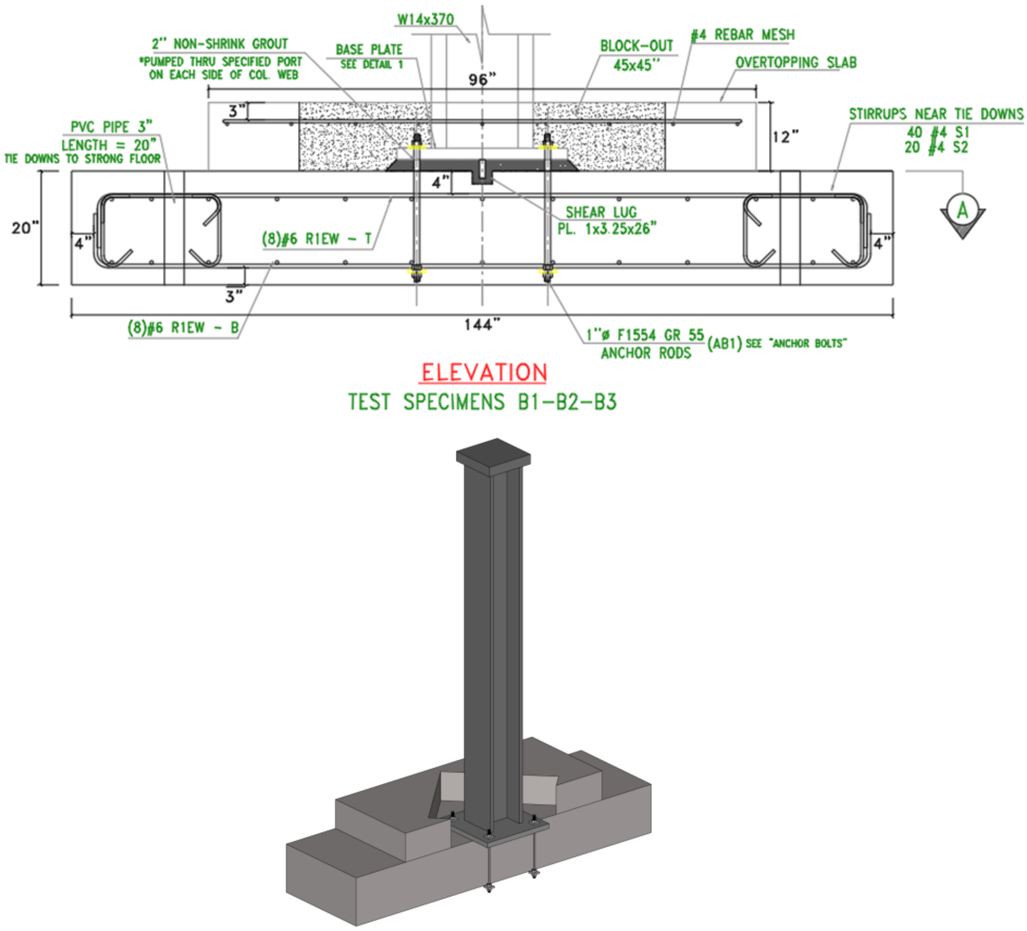

Fig. 3 – B-Series (Slab-overtopped) connection details

Four other tests (D-Series) represent the reliably ductile/dissipative exposed base connection with anchor rods specifically designed (as a below-ground fuse) to accommodate large inelastic base rotations accumulated over multiple seismic events. In this connection, the anchor rods have upset threads, wherein the diameter of the shank (unthreaded part) is reduced as compared to the diameter of the threads. This will keep the threads elastic, forcing the yielding action in the rod's reduced section (weak point). To accommodate the free movement of the rod through yielding action, the shank of the rod is de-bonded from the concrete by applying a polyethylene tape before the slab is poured, as shown in Fig.4.

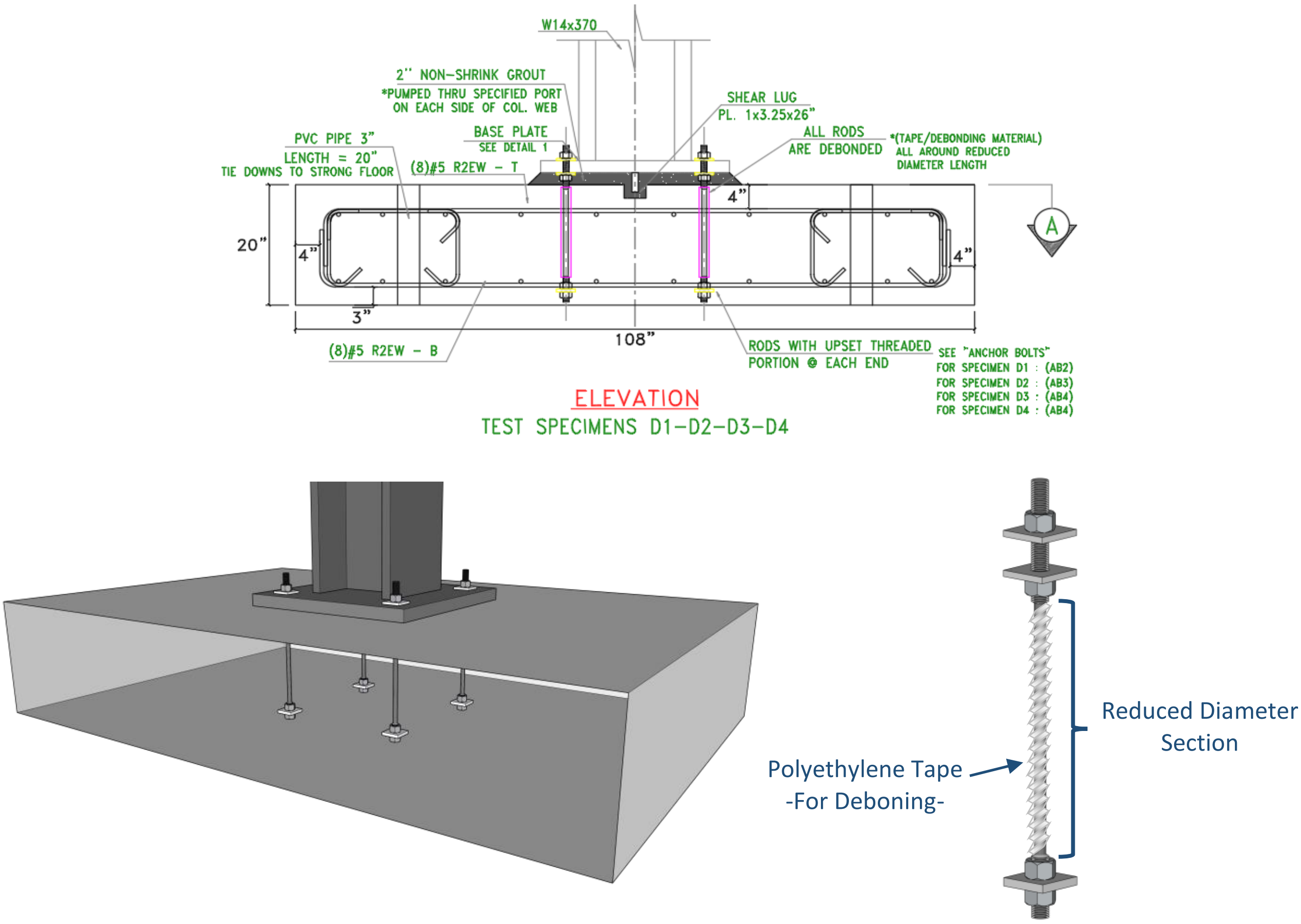

Fig. 4 – D-Series (Ductile/Dissipative) connection details with special anchor rod detailing

3.2 Test Setup

For seismic load simulations, horizontal loading is applied on the column's top through a horizontal actuator; for axial load application, a vertical frame is positioned above the column and affixed to clevis joints at the base, illustrated in Fig.5. The clevis joints allow free movement of the entire loading frame, such that the column is loaded to ensure the axial load is a "follower force". The concrete blocks (representing the column base concrete foundation) are tied to the laboratory strong floor using three dywidag anchors on each end. All dywidag anchors are prestressed to 50% of yield, such that the primary mechanism for shear transfer to the laboratory floor is friction with the concrete specimen. Concrete blocks with different heights are used to account for the differences in the two test series' configurations (B-Series and D-Series).

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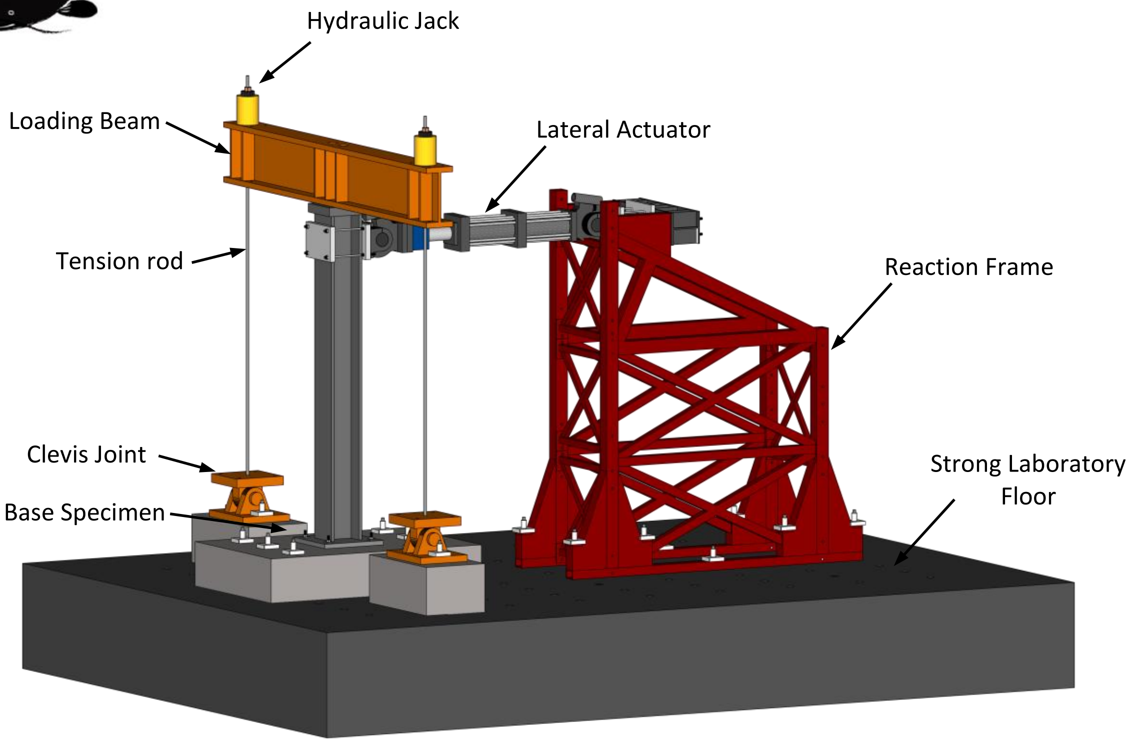

Fig. 5 – Test Setup for specimens with axial compression for D-Series (likewise for B-Series)

3.3 Instrumentation

Sufficient instrumentation is installed to acquire data relevant to characterizing the connection behavior, and to aid in the development of general design methodologies. The primary source of data is a cable transducer (i.e. string potentiometer) located along the line of action of the applied lateral load, providing load-displacement hysteresis curves for each test. Additional transducers are installed to detect out of plane motion of the loading frames, as well as unanticipated out of plane and torsion motion of the column, as shown in Fig.6.

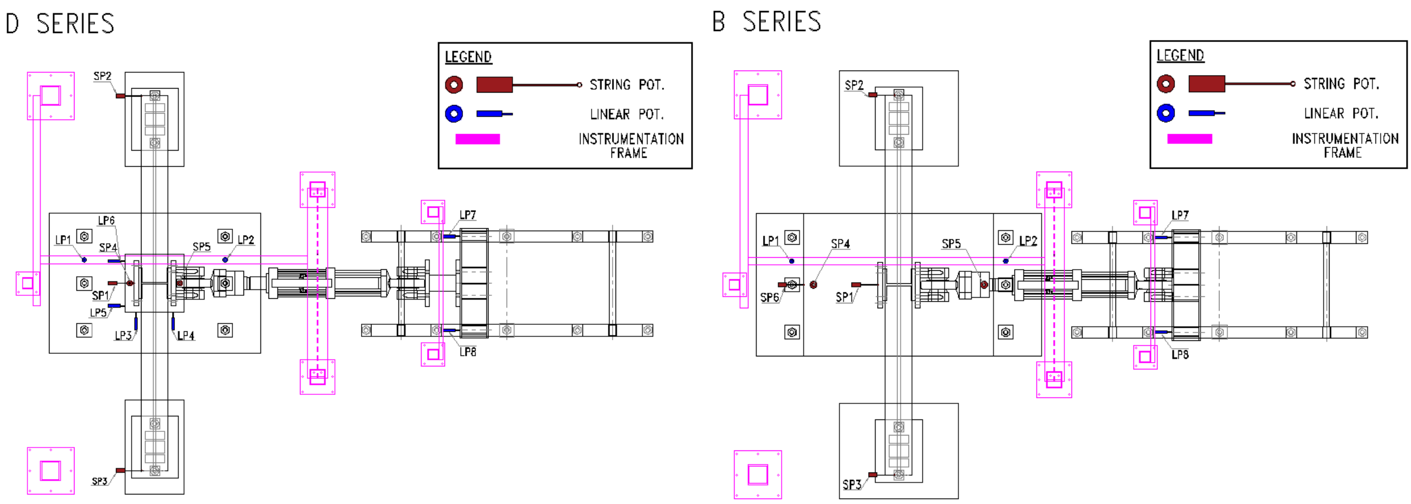

Fig. 6 – Instrumentation plan schematic for D-Series and B-Series tests (cable and linear transducers)

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Secondary data is acquired using strain gauges installed on both sides of each anchor rod embedded inside the concrete pedestals, to recover the strain profile along the length of the embedded anchors, illustrated in Fig.7. Additional strain gauges are installed on the bottom of the column flange, to supplement the load-displacement data, as well as on the base plate near the column flange, to detect bending and upward bearing from the grout and concrete.

All strain gauges for anchor rods are coated with water-proofing materials and silicon-based coatings prior to casting in the concrete blocks, as in Fig.7.

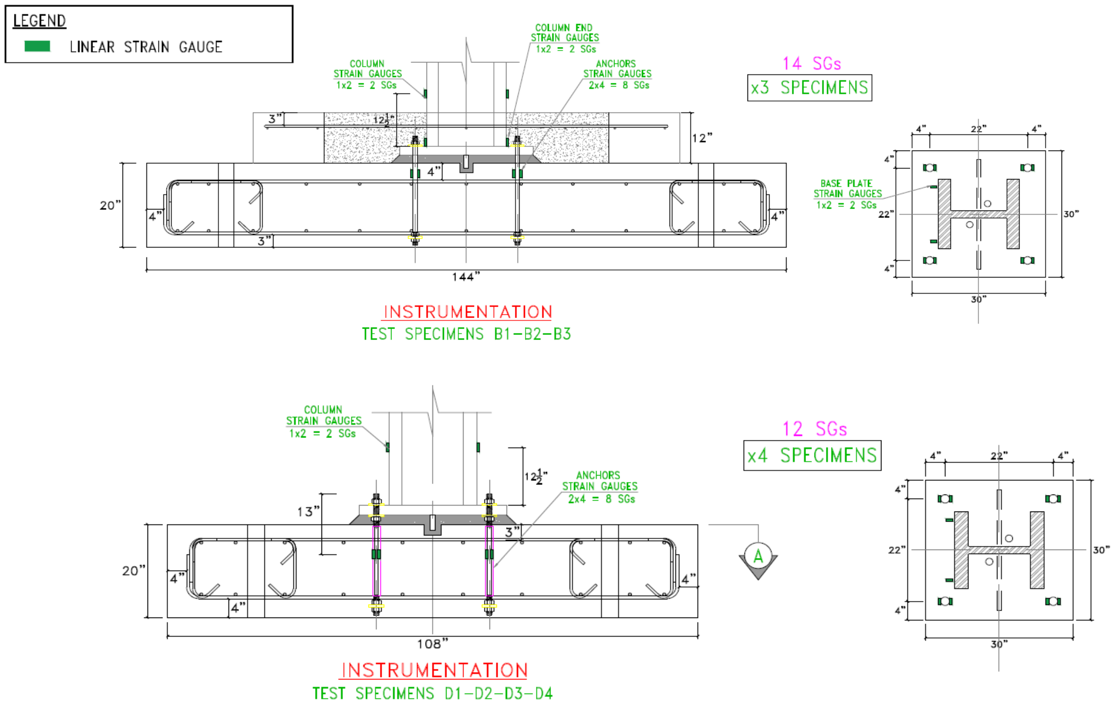

Fig. 7 – Strain gauges installation plan for D-Series and B-Series tests

4. Intended Outcomes

The focus of this study is to meet the following objectives:

1- To develop design methods/procedures and criteria for shallowly embedded connections through advanced understanding of their force transfer mechanisms, resulting in economical and reliable column base connections.

2- To develop and investigate a design paradigm for reliably ductile base connections, allowing for inelastic deformation while providing acceptable frame performance.

3- To develop design aids, examples, software, and other tools to facilitate the adoption of these new design insights and methods by the engineering practice.

This project is ongoing. The presentation will include new results, detailed analysis, and conclusions.

5. Acknowledgements

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