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Influence of base-plate connection stiffness on the design of low-rise metal buildings

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ABSTRACT

The objective of this research is to evaluate the influence of column base-plate connection rotational stiffness on the design of low-rise metal building systems. Currently, low-rise metal buildings are designed based on a zero rotational stiffness (pinned connection) assumption at the column-bases. Although prior research indicates that the assumption of zero rotational stiffness of the column base-plate connection could result in a significant underestimation of the overall lateral stiffness of horizontally loaded moment frames (leading to less economical designs), there has been no systematic study to investigate this issue. This paper first presents the details of an experimental research program that was conducted to quantify the rotational stiffness of “pinned” column base-plate connections that are commonly used in the low-rise metal building industry. Eight full-scale column base-plate connections with varying base-plate dimensions, numbers of anchor rods, anchor rod diameters, and gage distances were tested. Then, the data obtained were used to investigate the reduction in the total weight of gabled frames used in metal building construction. Finally, a piecewise nonlinear spring model was fitted to the test data to represent the rotational stiffness of the joints beyond the elastic range. Analyses of example frames indicate that consideration of the rotational stiffness of the pinned connections reduces frame deflections between 11 and 67% and has the potential to make metal building systems more economical by decreasing the frame weight between 0 and 12%, which is considered a substantial cost saving for the metal building industry where profit margins are relatively low.

1. Introduction

Low-rise metal building systems are widely used in the United States and worldwide as complex production facilities and warehouses, retail stores, shopping centers, schools, libraries and medical facilities for their cost effectiveness, easy fabrication and rapid construction. They account for 49% of the total non-residential low-rise construction market in the United States [1]. The buildings are typically made from built-up I-sections, commonly with tapered-webs [see Fig. 1(a) as an example of a gabled-frame in a low-rise metal building and Fig. 1(b) as an example of a web-tapered column]. The base-plate connections are commonly designed with the anchor rods placed inside the column flanges [see Fig. 1(c)], which leads to the “pinned” connection assumption. Thus, the rotational stiffness they might provide is ignored in the design of metal buildings.

The pinned (as opposed to semi-rigid or fixed) connections simplify the design and construction of the frames and the foundation. An asymmetric anchor rod arrangement is commonly used to simplify the fabrication of column bases and the anchor rod placement in the foundation. A typical setback (distance from the straight flange) is chosen between 64 and 102 mm (2.5 and 4 in.) depending on the size of the anchor rods. The setback is chosen such that the location of the first pair of anchor rods can easily be identified and there is enough clearance from the flange to turn a nut in the field. Then the pitch and gage are typically chosen as either 75, 100 or 125 mm (3, 4 or 5 in.) to help easily determine the location of the next set(s) of anchor rods on the base plate as well as to help with the placement of the anchor rods at a correct distance from each other in the foundation using a pre-prepared template. The setback from the inclined flange is then determined based on these parameters and the depth of the column. Since setback and pitch are determined based on mostly constructability issues, while the column depth is imposed by the serviceability and strength design, the result is an asymmetric anchor rod configuration, from a design perspective, which is no different than a symmetric anchor rod configuration since a pinned assumption is being made. However, as discussed later in

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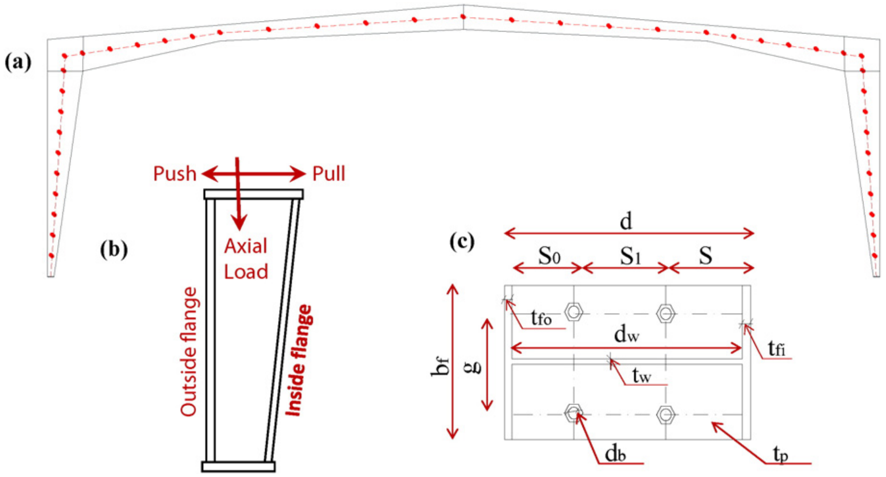

Fig. 1. (a) An example gabled frame used in low-rise metal building construction, (b) elevation view of the column stub, (c) base-plate connection details.

this paper, the connections exhibit considerable amount of rotational stiffness and strength. Additionally, the asymmetry of the connection and the taper of the column web results in asymmetric moment–rotation behavior of the bases.

The behavior of column base-plate connections depends on numerous factors including base-plate dimensions, anchor rod diameter and spacing, column cross-sectional dimensions, presence or absence of grout between the foundation and the base-plate, and the material properties of the steel and the concrete used for the frames and the foundation. The interaction of these factors controls the rotational stiffness, strength and ductility of these connections. The necessity to take into consideration the rotational stiffness of pinned column base-plate connections in a frame analysis was first pointed out by Galambos [2]. Since then, several experimental and analytical studies have resulted in the development of the American Institute of Steel Construction's (AISC) Steel Design Guide 1 [3], which contains detailed procedures for designing column base-plate connections subjected to different loading conditions.

The column base-plate configurations in which the anchor rods are positioned outside the flanges have been tested extensively [4–12]. These tests were generally conducted under an axial load, a bending moment, or both, to investigate the plastic behavior of the column base-plate connections. In contrast, relatively few studies experimentally evaluated the rotational stiffness of base-plate connections that are designed to be nominally pinned [7,9,13–15]. Pinned base-plate connections have also been tested as a part of full-scale frames by Hong [16] and Bajwa et al. [17]. A considerable rotational stiffness of the column base-plate connections was reported.

The interaction between the anchor rod size, base-plate thickness, and load eccentricity was studied by DeWolf and Sarisley [18] and Thambiratnam and Paramasivam [19]. The experimental observations of these studies on column base-plate connections with a single anchor rod showed that the increase of the base-plate thickness leads to the decrease of the connection capacity since the base-plate behaves like a rigid plate resulting in large bearing stresses and premature failure in the concrete. In addition, when the anchor rod diameter is large relative to the base-plate dimensions, the anchor rods do not attain their full capacity prior to failure of the base-plate. This was especially true for connections with lower load eccentricities.

There have also been efforts to examine the behavior of column base-plate connections using numerical techniques. Detailed finite element models were developed to quantify the "partial rigidity" of pinned column base-plate connections [17,20]. These were correlated with experimentally obtained rotational stiffness. Several studies have found that the consideration of the base restraint could lead to non-negligible benefits in terms of reduced service deflections and strength demands in the design of the frames [17,21,22]. Particularly, Eroz et al. [21], by modeling the partial-restraint of the base connections with two rotational springs in series (representing the base and the foundation), commented that the frame service deflections and the member strength demand were reduced by 3–9%.

2. Research significance

This study focuses on characterizing the rotational stiffness of pinned base-plate connections [see Fig. 1(c)] that are commonly used in metal building systems and its influence on the structural design. All the connections tested as a part of the experimental program had asymmetric anchor rod arrangements with respect to the center of the base-plate and the length of the base-plate was equal to the column section depth (i.e., overhang equals to zero). Thus, the tested configurations were distinctly different from those in the literature and represent

Table 1
Dimensions of the tested base-plate connections [refer to Fig. 1(c)].

Specimen ID	Base-plate width	Base-plate depth	Base-plate thickness	Web thickness	No. of anchor rods	Anchor rod diameter	Outside flange thickness	Inside flange thickness	Web depth	Setback	Pitch	Setback	Gage	Axial load
	b_f (mm)	d (mm)	t_p (mm)	t_w (mm)	–	d_b (mm)	t_{fo} (mm)	t_{fi} (mm)	d_w (mm)	S_0 (mm)	S_1 (mm)	S (mm)	g (mm)	(kN)
S1	152.4	271.5	12.7	4.0	4	19.1	7.9	9.5	254.0	76.2	101.6	93.7	101.6	93
S2	203.2	322.3	15.9	6.4	6	19.1	9.5	7.9	304.8	76.2	101.6	144.5	101.6	116
S3	203.2	320.7	15.9	4.0	4	19.1	6.4	9.5	304.8	76.2	101.6	142.9	101.6	229
S4	203.2	282.6	15.9	6.4	4	25.4	12.7	15.9	254.0	101.6	101.6	79.4	101.6	285
S5	152.4	304.8	9.5	2.9	4	19.1	6.4	6.4	292.1	76.2	101.6	127.0	101.6	48
S6	203.2	320.7	15.9	4.7	4	19.1	6.4	9.5	304.8	76.2	101.6	142.9	101.6	300
S7	254.0	273.1	12.7	4.7	4	19.1	9.5	9.5	254.0	76.2	101.6	95.3	101.6	174
S8	254.0	355.6	19.1	4.7	4	31.8	9.5	15.9	330.2	101.6	127.0	127.0	127.0	194