Column Base Connections: Research, Design, and a Look to the Future

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This paper is based on the 2022 T.R. Higgins lecture.

ABSTRACT

Column base connections are critical to the performance of steel structures, serving as the interface between the steel superstructure and concrete foundation. Historically under-researched, these connections have received significant attention over the past two decades, leading to major advances in understanding their strength, stiffness, seismic behavior, and simulation. This paper provides a synthesis of these developments, focusing on exposed and embedded base connections across a range of loading conditions and structural configurations. Key contributions include improved strength models, detailed assessments of seismic performance, and the introduction of modeling tools now included in the 3rd Edition of AISC Design Guide 1. The paper discusses elastic and inelastic behavior, base connection–frame interaction, and the emerging use of base connections as yielding elements in seismic design. Advances in simulation of base connections, including rotational spring and line-element-based models, enable more accurate structural simulations. Despite this progress, notable gaps remain, including the behavior of braced frame connections, foundation-soil interaction, and performance-based design for repairability and resilience. This work aims to consolidate recent findings, inform ongoing research, and guide future design practices toward a more integrated treatment of base connections in steel structures.

Keywords: base connection, moment frames, composite connection.

INTRODUCTION

Column base connections are arguably the most critical connections in steel buildings because they transfer forces from the entire structure into the foundation. They are essential in every steel building, regardless of the structural system or type of loading. While their forms can vary significantly, depending on their function (e.g., moment frames versus braced frames) or the magnitude of the load (leading to exposed versus embedded connections), they are always located at the interface between steel and concrete. This interface makes both their behavior and design particularly interesting and complex because these connections are inherently composite in nature (i.e., internal forces are carried by both steel and concrete and the interfaces between them). In fact, base connections exist not only at a physical boundary, but also at a disciplinary one, between the steel and concrete trades, where research and standards development often occur independently. Furthermore, base connections interact with the structure affecting its response. These behaviors influence not only the design of the connections, but also the performance and design of the entire structural system.

Figure 1 illustrates base connection details commonly used in U.S. construction practice. Historically, research on base connections has lagged behind that of other structural connections. This is particularly notable given their critical role. However, over the past two decades, there has been a substantial increase in global research attention, leading to significant advances in multiple areas, including: (1) improved understanding of failure modes and the development of strength models for various base connection configurations; (2) evaluation of seismic performance and its implications for both connection and system-level design; (3) development of simulation methodologies tailored specifically to base connections; and (4) integration of research findings into practical design tools, such as manuals and software, notably, the release of the 3rd Edition of AISC Design Guide 1, *Base Connection Design for Steel Structures* (Kanvinde et al., 2024), published nearly two decades after the 2nd Edition (Fisher and Kloiber, 2006). The primary objective of this paper is to provide an overview of these developments, culminating in the current state-of-the-art understanding of base connections. Topics include behavioral characteristics, modeling strategies, design considerations, and emerging research needs and priorities. This paper accompanies the 2022 T.R. Higgins Lectureship Award presentation (of the same title) and expands upon the themes introduced in that lecture.

The paper begins by summarizing key research developments that have emerged since the publication of a landmark report (Grauvilardell et al., 2005) that offers a

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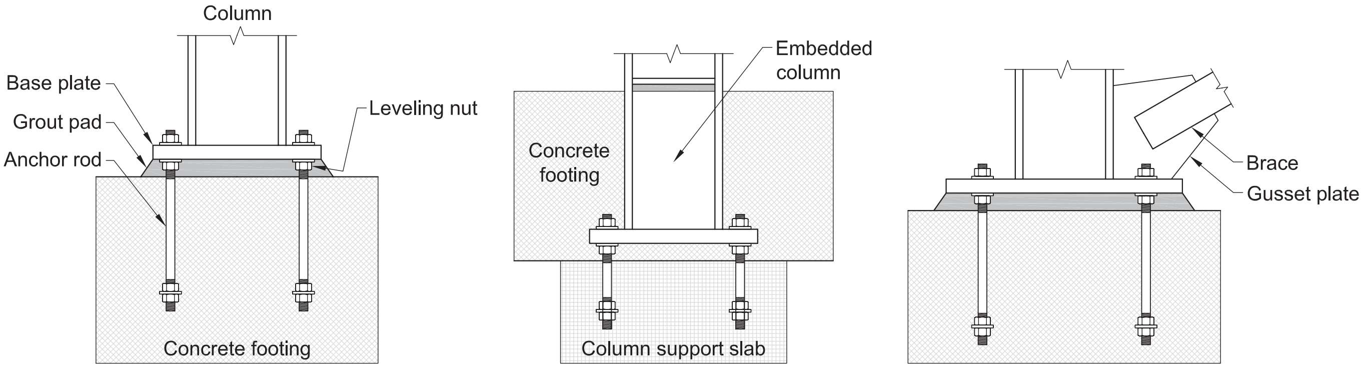
comprehensive overview of earlier work on base connections. This is followed by a discussion of the current state-of-the-art in three critical areas: (1) strength models and design approaches for various base connection configurations, (2) modeling of base connection behavior, and (3) seismic response and related design considerations. The narrative also describes how relevant advances in each area have been integrated into the 3rd Edition of Design Guide 1. The paper concludes by highlighting ongoing research, identifying remaining gaps in knowledge and design guidance.

RESEARCH DEVELOPMENTS

Figure 2 illustrates the number of articles published over the past several decades on the general topic of column base connections or base plates. Notably, there is a marked increase in publications following the release of the Grauvilardell et al. (2005) report, suggesting its significant role in catalyzing research in this area. A closer look at these studies reveals that the surge in interest was global, with substantial contributions from researchers in the United States, Europe, Asia, and South America. This body of work can be broadly categorized into three areas: (1) studies on exposed column base plate connections, (2) studies on embedded column base connections, and (3) investigations into the interaction between base connections and the structural frame. The findings from these studies have been integrated to develop strength models, modeling guidance, and design philosophies—particularly in the seismic context—that leverage the available deformation capacity of base connections. This section provides a brief overview of the research conducted since 2006, while the remainder of the paper synthesizes the key findings and implications of this work.



(a) Exposed base plate *(b) Embedded base* *(c) Connection with brace*

Fig. 1. Column base connections commonly used in the United States.

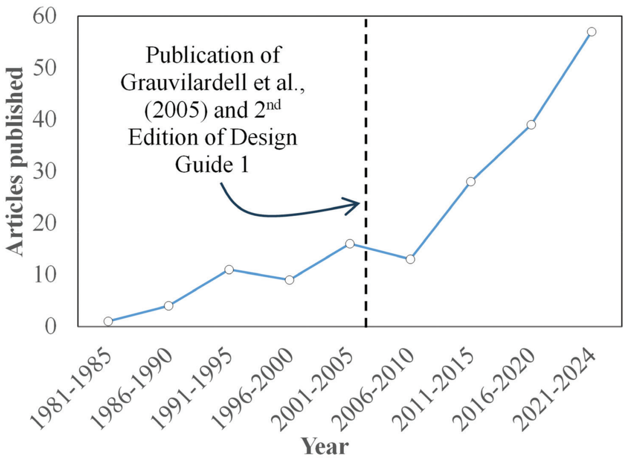


Fig. 2. Articles published on the topic of column base connections during each 5-year period between 1981–2024 (Source: EI-Compendex database with "Column base connections"and related keywords).

A significant portion of research on base connections has focused on exposed base plate connections, such as the configuration shown in Figure 1(a). Much of this work has addressed base connections without braces or gusset plates and has included large-scale experiments by Gomez et al. (2010), Kanvinde et al. (2014), Trautner et al. (2017), and Hassan et al. (2022). These U.S.-based studies are complemented by similar work in Europe (e.g., Wald et al., 2008; Gresnigt et al., 2008; Di Sarno et al., 2007), which has expanded the experimental database for model development and validation. Additional studies from Japan (Choi and Ohi, 2005), South Korea (Choi and Choi, 2013), and France (Seco et al., 2021), as well as from Fasaee et al. (2018), have examined base plates under biaxial bending and axial compression. These experimental efforts have been supported by finite element analyses, which help generalize findings to untested configurations and offer insight into internal force distributions and design strategies.

In contrast, research on embedded base connections was limited prior to 2006. Since then, significant progress has been made on both deeply embedded (Grilli et al., 2017; Hassan and Kanvinde, 2023) and shallowly embedded or "blockout" (Barnwell, 2015; Hassan et al., 2024; Hanks and Richards, 2019) configurations, along with related work in Japan (Cui et al., 2009). As with exposed connections, this body of research has informed strength, stiffness, and load-deformation models. Finally, notable advances have been made in understanding the seismic performance of base connections in moment frame systems. Collectively, these developments have been synthesized into the 3rd Edition of Design Guide 1.

Another important area of research involves the simulation of base connections, particularly their rotational response (both in terms of initial stiffness and hysteresis) and its effect on member and frame response. For example, Kanvinde et al. (2012), Richards et al. (2018), and Torres-Rodas et al. (2017) present stiffness models, while Torres-Rodas et al. (2016), Torres-Rodas et al. (2018), and Villar-Salinas et al. (2024) provide nonlinear load-deformation models. These models have been validated at multiple scales, including through studies of instrumented buildings (Falborski and Kanvinde, 2022), and have informed the development of design considerations for base connections under seismic loading. Research in this area continues to evolve, addressing several unresolved questions that are discussed in the concluding section of this paper.

STRENGTH MODELS AND DESIGN

Almost all research on column base connections has been for connections without braces; this is the focus of discussion in this section. Within this, exposed type base plate connections are first addressed, followed by embedded type base connections. Some discussion of base plates with braces is also provided at the end of this section.

Exposed Base Plate Connections without Braces

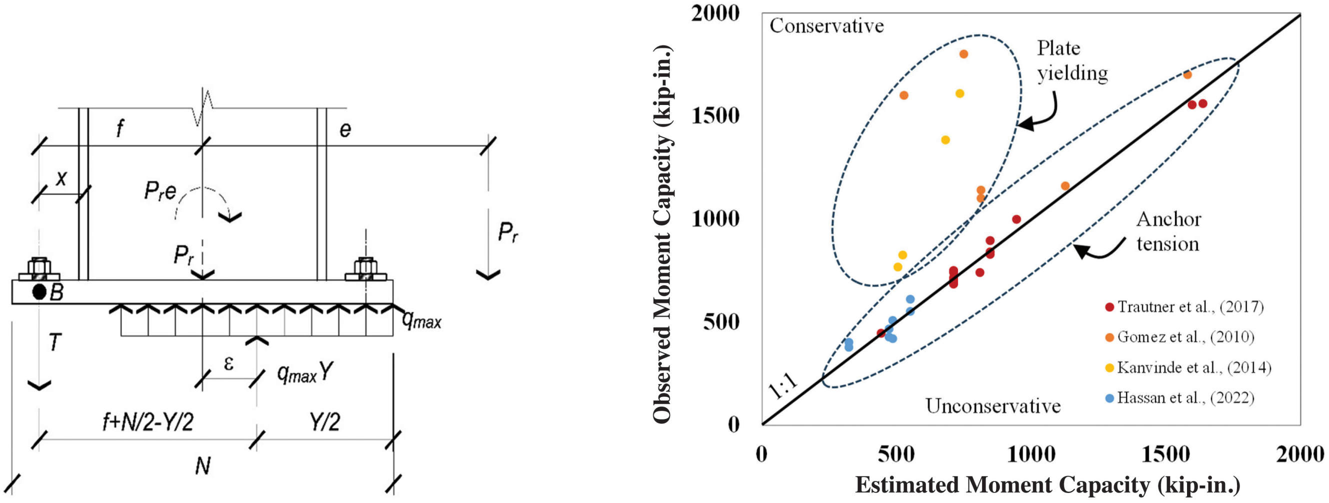
The design of exposed base plate connections, wherein a steel column is welded to a base plate anchored to a concrete footing using cast-in or post-installed anchors, has been the focus of the first two editions of Design Guide 1, as well as a majority of prior research. The design process generally involves two key steps: (1) estimating the internal stress or force distribution within the connection and (2) evaluating potential limit states in various components resulting from this distribution. The internal stress distribution arises from complex mechanics, involving phenomena such as contact and separation between components, nonlinear behavior of the footing materials, and deformation of both the base plate and anchors. Except in very simple cases where anchor forces may be assumed equal—such as a rigid base plate in pure tension—estimation of internal force distribution is nontrivial.

For typical base connections subjected to axial load (usually compression) and flexure, the method developed by Drake and Elkin (1999) is widely used. This approach simplifies the connection mechanics by representing the bearing stress in the concrete as a triangular or rectangular stress block [see Figure 3(a)]. This results in a system of two equilibrium equations that can be solved to determine the anchor forces [denoted T in Figure 3(a)] and the width of the bearing stress block [denoted Y in Figure 3(a)]. Once the internal forces are known, they are used to evaluate the following limit states: (1) flexural yielding of the base plate at both the bearing and tension faces, (2) anchor yielding or concrete failure, and (3) concrete crushing in the footing. The concrete limit states at the base plate bearing interface, and the anchorage into the concrete on the tension side are evaluated following the requirements of ACI 318 (ACI, 2019) code requirements for structural concrete and commentary. Figure 3(b) illustrates assumptions underlying the method, which was developed based on engineering judgment prior to much of the testing on base connections. Specifically, Figure 3(b) compares the estimated moment strengths from 35 large-scale tests conducted at UC Davis and UC San Diego with predictions from the Drake and Elkin (1999) method (using the rectangular stress block model) as presented in Design Guide 1. The figure also indicates the predicted failure mode for each test.

A closer examination of the results and underlying test data [not shown here, but see the references in the legend in Figure 3(b)] indicates that the method is accurate or conservative. It is particularly noteworthy that this level of agreement is achieved by a method developed without the benefit of experimental calibration, reaffirming the value of fundamental engineering principles and judgment. In cases where anchor rod yielding governs, the method demonstrates near-perfect accuracy. Conversely, the method is more conservative when plate bending governs. In fact, when flexural yielding of the base plate controls the response, the method tends to significantly underpredict strength due to several factors: (1) When the plate yields in flexure on the bearing side, a complete failure mechanism does not form until another limit state is reached, typically flexural yielding of the base plate on the tension side or anchor rod yielding, or until bearing failure occurs in the footing. (2) The assumed bearing stress distribution under the plate often does not reflect actual stresses, which tend to concentrate under the column flange, leading to inaccurate estimates of the bending moment in the plate. (3) When flexural yielding occurs on the tension side, the base plate tends to exhibit significant strain hardening. However, this latter failure mode should be avoided because it can cause kinking of the plate beneath the column weld, increasing the risk of fracture.

In addition, the approach in Design Guide 1 presents several broader limitations, some of which have been addressed in subsequent research and must be considered in its application. First, the approach—particularly its rectangular stress block (RSB) variant—assumes that the bearing capacity of the footing (denoted q_{max}; see Figure 3) is fully mobilized even at relatively low applied moments, as long as the moment-to-axial load ratio indicates "high eccentricity." While this assumption is useful and often necessary for simplified analysis, it can yield unrealistic results when the applied moment is insufficient to mobilize the footing bearing capacity. Such situations are not uncommon and can significantly affect downstream calculations, especially in estimating anchor rod forces and the associated uncertainties. These estimates are particularly sensitive to the assumed bearing stress distribution and its variability; see Song et al. (2020) for further discussion. Second, the approach is limited to a specific configuration: a base plate subjected to uniaxial bending with a single row of anchor rods in tension. It does not extend to cases involving biaxial bending [addressed by Fasaee et al. (2018) and Hassan et al. (2021) and included in the 3rd Edition of Design Guide 1], multiple rows of anchors, circular columns, or nonrectangular base plates. Furthermore, it does not account for effects such as prying action, which may occur when base plates extend significantly beyond the anchor rods.

Recognizing that a single analytical method cannot accommodate all possible configurations, there is growing interest in the use of conventional finite element models and, more recently, the component-based finite element method (CBFEM), for such analyses (Sabatka et al., 2014). These methods offer the potential to overcome many limitations of analytical approaches, especially when they can accurately simulate underlying physical behavior, such as contact interactions and material responses. However, the reliability of their results depends heavily on a range of modeling assumptions, including component geometry idealization, element selection, contact definitions, and material constitutive models. As such, careful application and benchmarking against experimental data are essential. Appendix D of Design Guide 1 outlines several considerations for the effective use of finite element modeling in base connection analysis.



(a) High-eccentricity case

(b) Results applied to test data

Fig. 3. Drake and Elkin method.

Embedded Base Connections

Figure 1(b), shown previously, illustrates embedded base connections. These may be specified in two situations:

1. When the design forces and moments are large enough that transferring them through exposed base plate connections becomes unfeasible or prohibitively expensive. This is typically due to the need for a large number of heavy anchors and a thick base plate. In such cases, embedding the base offers a more practical alternative. However, this approach involves a tradeoff: It requires two separate concreting operations—first to erect the column base and then again to complete the embedment, adding both time and cost. These are referred to as "deeply embedded column bases—DECB" in this paper and are shown in Figure 4.
2. When a slab-on-grade is poured over conventional exposed base plate connections to achieve a smooth finished surface. In this case, the embedment (whose thickness is equal to the slab depth) is incidental rather than intentional and is not specifically designed to provide strength. These are denoted "shallowly embedded column bases—SECB" or "blockout" connections, owing to the diamond-shaped blockout that is placed around the columns during installation of the floor slab to facilitate subsequent column erection and a second concrete pour within this blocked out region, as shown in Figure 5.

In both scenarios, however, the embedment provides additional strength and stiffness. In the first case, this contribution is critical and must be explicitly considered in the design. In the second case, although the added strength is unintentional, it can significantly affect seismic performance assessments. When multiple such incidental embedments are present in a structure (e.g., at the bases of gravity frames), their cumulative effect on overall resistance can be considerable.

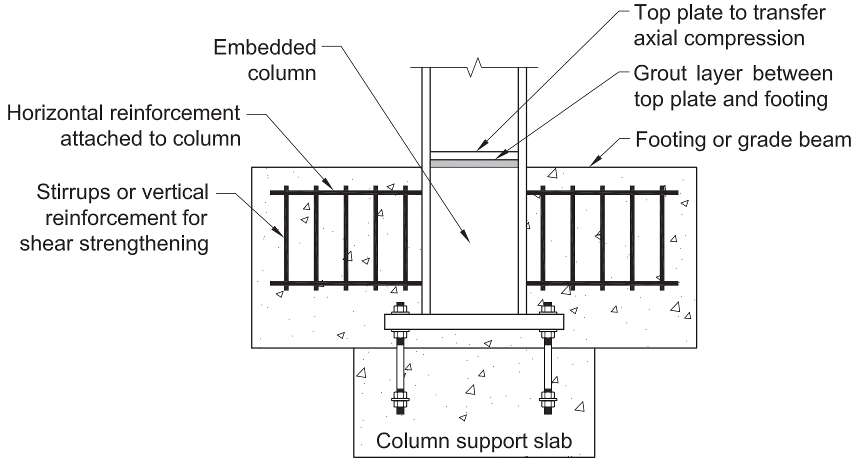


Fig.4. Deeply embedded column base connection.

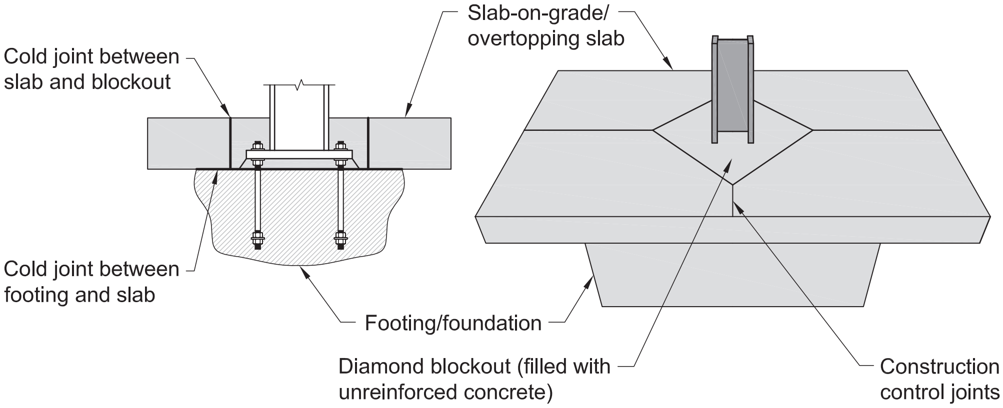
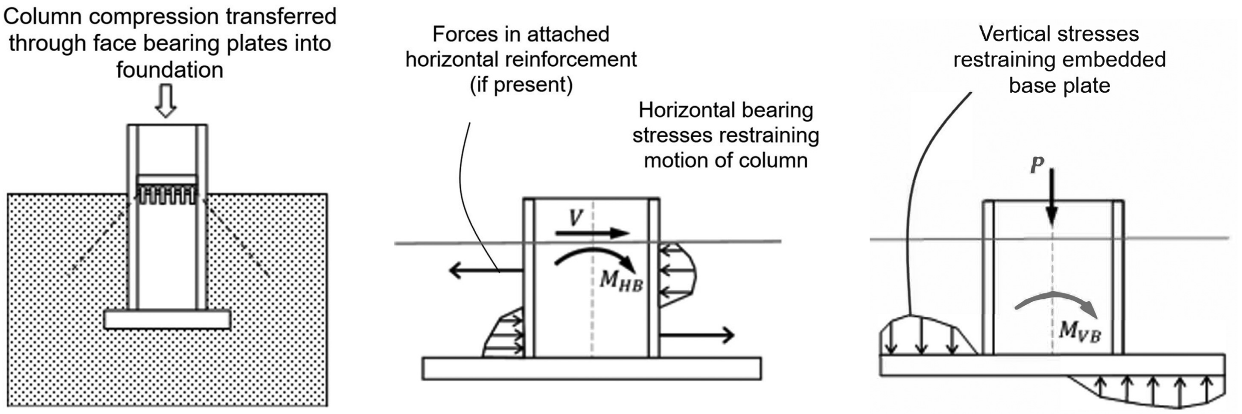


Fig. 5. Blockout connections resulting in shallow embedment of base plate connection.

Research on embedded base connections has been relatively limited, with most studies emerging only in recent years. As a result, formal design guidance has also been lacking. In the absence of definitive research, design guidelines for embedded connections, specifically the AISC *Seismic Design Manual* (AISC, 2018), have largely relied on engineering judgment informed by observed structural behavior and design methodologies developed for steel brackets or coupling beams embedded in concrete shear walls (Mattock and Gaafar, 1982; Shahrooz et al., 1993). However, research including experimental and analytical studies conducted in the United States (e.g., Hassan and Kanvinde, 2023; Grilli et al., 2017; Richards et al., 2018), Japan (Cui et al., 2009), and Europe (Pertold et al., 2000a, 2000b; Inamasu et al., 2020) has significantly advanced the understanding of internal force distributions and contributed to the development of more accurate strength models. The models—specifically their mathematical formulations and other relevant details—are discussed in the references just cited. Figure 6 illustrates the internal force distribution (inferred from physical experiments as well as finite element simulations) in DECB connections.

The main observations are as follows:

1. Compressive axial forces are resisted through a properly designed load path, either via stiffener-type plates provided at the top of the connection [see Figure 6(a)] or a conventional base plate, assuming the foundation below is adequately designed to transfer these forces. Tensile forces are most effectively resisted by the lower base plate bearing upward against the footing.
2. Applied moments are resisted by a combination of horizontal and vertical reactive forces acting on the embedded portion of the column. This is in contrast to assumptions inherent in commonly used approaches that idealize embedded connections as steel coupling beams, in which only the resistance due to the horizontal bearing stresses on the column flanges is active. The moment [M_{HB} in Figure 6(b)] is resisted by horizontal forces—that is, bearing stresses on the column flanges, as well as forces transmitted through any attached reinforcement [see Figure 6(b)]. The moment resisted by vertical stresses (denoted M_{VB}) consists of bearing stresses on the embedded base plate [Figure 6(c)] and the forces carried by anchor rods, if such rods are provided to secure the lower base plate.
3. The proportion of the moment resisted by each mechanism depends on the embedment depth; greater embedment typically results in a larger share of the moment being resisted by horizontal forces. Grilli and Kanvinde (2017) and Hassan and Kanvinde (2023) outline methods for quantitatively estimating these in DECB connections; these stresses are governed by the flexural stiffness of the embedded column relative to the reactive stiffness of the surrounding footing material, particularly the stiffness associated with horizontal bearing stresses. Hassan et al. (2024) provide similar analysis for SECB/blockout connections.
4. Based on the internal force distributions, various limit states may be evaluated to estimate the connection strength. These include (a) mobilization of bearing capacities (for horizontal stresses, this depends on the concrete strength and confinement effects; for vertical stresses, it is often governed by the breakout strength of the concrete above the base plate as it experiences uplift) and (b) resistance of reinforcement or anchors (the contribution of any embedded reinforcement attached to the column flanges or anchors attached to the base plate must also be considered).



(a) Axial compression *(b) Horizontal bearing* *(c) Vertical bearing*

Fig. 6. Internal force transfer in embedded base connections.

5. Recent experiments (Hassan et al., 2024), reveal some nonintuitive aspects of the connection response that are important to consider in design. Specifically, in configurations where horizontal reinforcement is attached to the column flanges to enhance moment resistance, the reinforcement does increase horizontal strength. However, it also induces a tension field in the footing above the base plate. This creates a tradeoff: while horizontal reinforcement improves moment capacity, it concurrently decreases uplift strength of the underlying base plate due to the development of this tension field. The net effect of this tradeoff depends on the overall connection configuration and the presence of stirrups or shear reinforcement that can mitigate uplift reduction. Given the difficulty in reliably estimating the uplift resistance in such cases, it may be conservative to disregard the contribution from vertical forces altogether when horizontal reinforcement is provided.

These approaches are described in the 3rd Edition of Design Guide 1 along with a demonstrative solved example. Additionally, software tools are provided in the Design Guide 1 bonus materials on the AISC website to assess the strength of DECB connections and facilitate design.

Base Connections with Attached Braces

Research on base connections with attached braces, such as the one shown in Figure 7 (commonly found in braced frames), is virtually nonexistent. Consequently, strength models and design approaches for these connections are typically based on generalizations of behavior and internal force distributions inferred from connections without braces, as discussed in the preceding sections.

While such extrapolations are expedient, it is important to recognize that several key differences between braced and unbraced connections may influence internal force distributions and limit states. First, the presence of a gusset plate required to attach the brace often results in an asymmetric base plate layout and a corresponding asymmetry in stiffness distribution—with a potential for unanticipated internal force distributions. Second, base connections with braces frequently use six- or eight-anchor configurations, placing them outside the scope of the methods outlined in Design Guide 1. Finally, while connections in braced frames are often designed as pinned (and modeled as such in structural analysis), they have significant rotational restraint provided by the anchors, the gusset, and the plate. This unintended stiffness could attract moments to the connection and induce additional forces in the anchors that are not accounted for in current design practices.

SIMULATING BASE CONNECTIONS

Simulation of base connections can be considered in two principal contexts: (1) simulation of the connections themselves to characterize internal force distributions (e.g., for the design of anchors or other subcomponents) when configurations fall outside the scope of Design Guide 1 or other guidance and (2) representation of base connections within frame simulations of the overall structure. This paper focuses on the latter, recognizing that the load–deformation behavior of base connections significantly influences global structural response, with critical implications for seismic design, as discussed in the following section. The former is addressed in detail in Design Guide 1, Appendix D. The moment–rotation response is of primary interest in

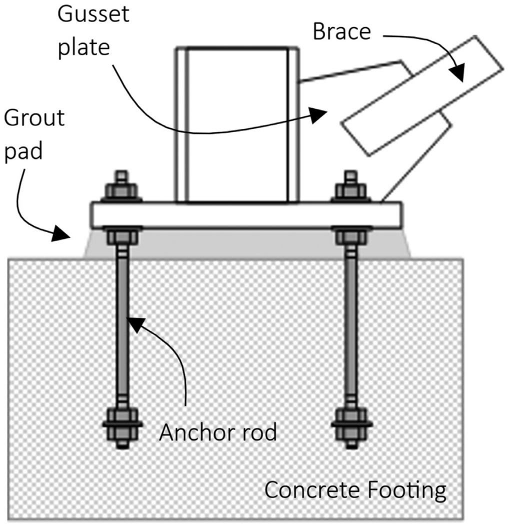


Fig. 7. Column base connection in a braced frame.

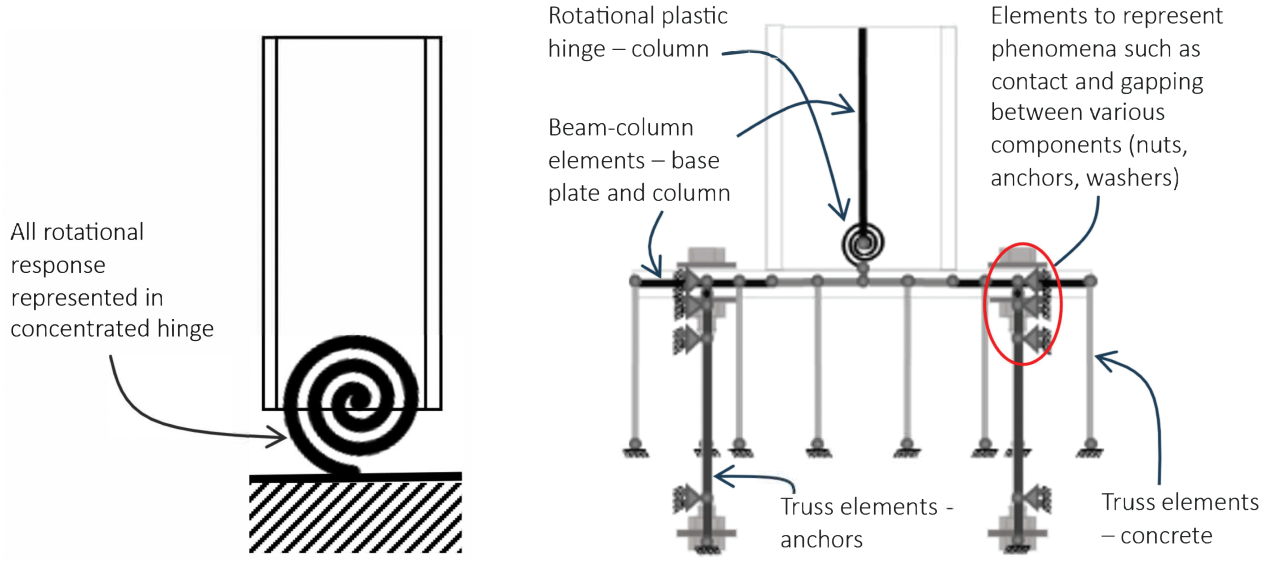
structural simulations; however, responses along additional degrees of freedom (e.g., uplift or axial force and deformation) and their interaction with moment–rotation behavior are also relevant. The primary emphasis here is on the elastic response of base connections because they are typically designed to remain elastic under service conditions. Nevertheless, growing interest in leveraging their inherent ductility for seismic applications has increased the need to simulate their inelastic behavior as well. Two classes of models have been used effectively to simulate column base response: (1) rotational hinge models calibrated to reproduce moment–rotation behavior and (2) line element–based models—often termed "hook and gap" models—that simulate individual connection components (e.g., anchors or base plates) using beam–column elements. Each approach (illustrated schematically in Figure 8) is discussed in the following, with emphasis on validated methodologies and best practices.

Rotational Spring Models

Rotational spring models idealize the behavior of column bases as purely rotational, following well-established methodologies similar to those used for modeling plastic hinges in beam-columns (Lignos and Krawinkler, 2011). While the complete load-deformation response, including nonlinear monotonic and hysteretic behavior, is relevant in scenarios where base yielding is anticipated, this study focuses on the elastic rotational stiffness of base connections because this property is frequently of primary interest in design and analysis. A recurring question in structural simulation, whether for elastic design or nonlinear performance assessment, is whether base connections should be idealized as pinned or fixed. It is critical to recognize that base connection stiffness, in absolute terms, cannot be inherently classified as either pinned or fixed. Instead, its role must be evaluated in relation to the global structural response and the specific performance metrics of interest, such as interstory drift or internal forces and moments in the members. Accordingly, it is generally more accurate to model the base connection explicitly as an elastic rotational spring, incorporating an appropriate estimate of stiffness.

Until recently, reliable methods for estimating this stiffness were limited. However, recent advances, drawing from physical testing (including those cited in previous sections) and vibration measurements of instrumented buildings (Falborski et al., 2020a), have led to the development and validation of practical stiffness estimation approaches. The underlying model formulations are presented in Kanvinde et al. (2012), Torres-Rodas et al. (2017), and Richards et al. (2018). These models are mechanistic in nature, based on a rational understanding of internal force distributions under applied loads, combined with the aggregation of estimates of deformations across the various connection components under applied loads. User-friendly tools are now available in the form of downloadable executables on the AISC Design Guide 1 webpage, enabling convenient estimation of base rotational stiffness for a variety of connection types, including exposed base plates, embedded connections, and blockout configurations.

As expected, the rotational stiffness of a base connection is primarily governed by connection configuration along



(a) *Rotational hinge based* (b) *Line-element based*

Fig. 8. Representation of column base connections in frame simulations.

with the dimensions and material properties of key subcomponents such as anchors, base plate, and the footing. In addition, one of the most influential factors is the level of axial compression in the connection. Specifically, high axial compression inhibits uplift of the base plate under rotational loading, thereby significantly increasing the rotational stiffness. However, a purely rotational spring model cannot directly capture the influence of axial force because it is limited to a single rotational degree of freedom. In such cases, a practical approach is to calibrate the effective rotational stiffness of the base connection as a function of the applied axial compression.

The aforementioned computational tools incorporate this dependency. Similar strategies have been employed in the past for modeling plastic hinges in beam-columns. While convenient, these calibrated models assume a constant axial force and therefore cannot account for the effects of varying axial loads—an important limitation, particularly under seismic loading conditions. In reality, the instantaneous behavior of the connection is influenced by the simultaneous variation of axial force and lateral displacement. Furthermore, rotational spring formulations do not account for vertical deformation or stiffness at the base, which can become significant under large axial tension due to overturning demands. These limitations are addressed by the line-element-based (LEB) models, which were illustrated previously in Figure 8(b) and are introduced in the following section.

Line Element Based Models

Line-element-based (LEB) models provide a detailed framework for simulating both the linear and nonlinear behavior of base connections. These models typically idealize the connection region using a series of uniaxial spring elements and elastic beam-column elements [see Figure 8(b)], allowing for the isolated representation of key mechanisms such as bearing, gapping, and plasticity. Unlike simplified rotational spring models discussed in the previous subsection, LEB models are capable of capturing the interaction between axial and lateral (flexural) loads, making them particularly well suited for analyzing complex base behaviors under seismic or cyclic demands. In addition to representing overall load-deformation response, LEB models provide an understanding of response internal to the connection (which is entirely absent from the rotational spring models), allowing for the examination of local quantities such as anchor forces and deformations. While these models are significantly more computationally efficient as compared to continuum finite element models (by a factor of roughly 20), it is important to note that they are slower as compared to rotational spring models. Nonetheless, they have been used with success in suites of nonlinear time history simulations (Song et al., 2023) for probabilistic performance assessment, and their run-time, especially if only elastic response is required, is negligible on modern computers. However, they do require detailed calibration of various properties, including the use of specialized elements such as gap elements. While beyond the scope of this article, Song et al. (2023) and Hassan et al. (2022) provide an overview of best practices in this regard.

SEISMIC DESIGN

Over the past two decades, experimental and analytical studies on base connections have yielded significant insights that enhance the seismic design not only of the connections themselves, but also of the structural frames they are a part of. This section focuses on base connections in moment-resisting frames, consistent with the emphasis of most prior research. According to the AISC *Seismic Provisions for Structural Steel Buildings* (AISC, 2022), seismic design of base connections can follow one of two approaches, illustrated in Figures 9(a) and 9(b): (1) the *strong-base* design, where the base connection is capacity-designed to exceed the strength of the attached column, ensuring that plastic hinging occurs within the column, and (2) the *weak-base* design, which permits inelastic rotations to occur within the base connection.

The strong-base approach typically results in more expensive connections because they must resist the high moments associated with column yielding, often necessitating embedded connections. Despite the higher cost, this method is frequently favored due to the limited design guidance available for detailing base connections to achieve the ductility required by the weak-base approach. The design of strong-base connections is conceptually straightforward because established strength-based design methodologies, such as those previously discussed, can be employed. In this approach, the flexural demand on the base connection is taken as the fully yielded and strain-hardened moment capacity of the connected column. However, it is important to recognize that even when capacity-designed based on column strength, and even when embedded, strong-base connections may exhibit considerable elastic rotational flexibility. In other words, connection strength should not be conflated with stiffness. Assuming these connections to be rigid can lead to unconservative estimates of first-story column moment demands and lateral drift. Accordingly, it is recommended that realistic estimates of connection fixity be incorporated into structural analysis and design, using the modeling approaches summarized in the preceding section.

If a weak-base design approach is adopted, the following questions must be addressed:

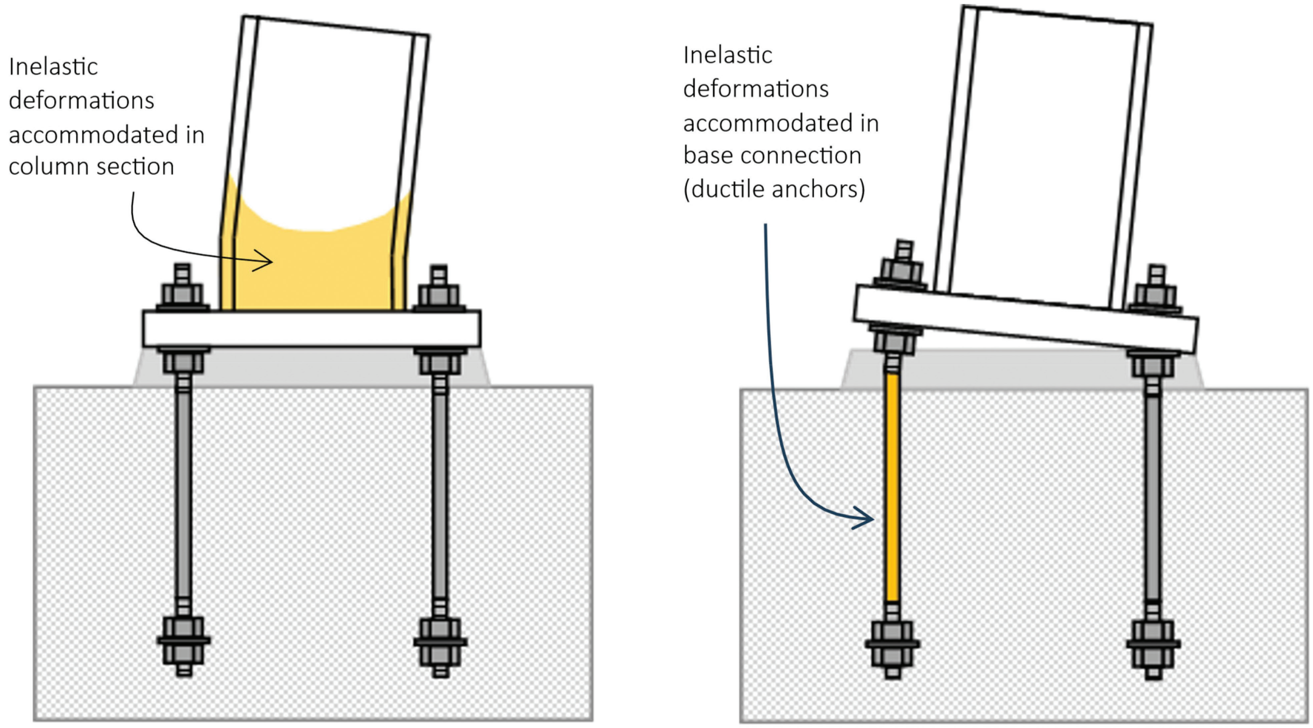
1. What loading conditions should the connections be designed for?

2. What level of ductility or deformation demand must they accommodate?
3. How will the required ductility capacity be achieved through practical detailing?

With respect to strength, as discussed earlier, current provisions (AISC *Seismic Provisions*) permit weak-base designs for moments corresponding to the overstrength seismic load (i.e., Ω_0). Additionally, a pinned-base condition (i.e., zero flexural strength at the base) is also allowed, provided that adequate shear strength is maintained. Research indicates that both approaches result in seismic performance (in terms of collapse resistance) comparable to that of strong-base designs. Further, studies (Falborski et al., 2020b) based on a limited set of archetype frames suggest that any base moment strength between fully pinned ($M = 0$) and strong base (i.e., $M_{base} \geq 1.1R_yF_yZ_{column}$) can deliver acceptable performance, provided the following three criteria are satisfied: (1) shear connectivity and resistance are maintained; (2) the moment capacity of the connection is sustained up to a target rotation—typically in the range of 0.04–0.05 rad; and (3) the first-story columns meet strong-column–weak-beam requirements, accounting for the lowered inflection point associated with a weak base.

Ongoing research aims to generalize these findings to support more flexible design provisions, enabling designers to select any base strength that meets these criteria. The ultimate goal is to move away from designing to a prescribed load demand and instead allowing engineers to optimize base strength based on project-specific tradeoffs, balancing the higher connection cost and reduced member demands of a stronger base against the lower connection cost and increased member demands associated with a weaker base.

Arguably the most critical consideration in the design of weak-base connections is ensuring sufficient deformation capacity through appropriate detailing. Encouragingly, experimental evidence indicates that base connections inherently possess substantial ductility, even when not explicitly designed for that purpose. Figure 10 presents the deformation capacities observed in specimens from seven experimental programs conducted over the past five decades. Despite variations in loading protocols among the studies, the overarching finding is consistent: Specimens across all programs demonstrated excellent deformation capacity (well over the 4–5% rotation demand anticipated in weak-base connections), rivaling or even exceeding the ductility typically required of beam-column connections.



(a) *Strong base*　　(b) *Weak base—anchor yielding*

Fig. 9. Seismic column bases.

It is noteworthy that among these programs, only the test series conducted by Hassan et al. (2022) incorporated upset-thread details with a smooth shank, specifically designed to enhance ductility. The 3rd Edition of Design Guide 1 provides detailed recommendations for proportioning and detailing to achieve such high ductility. While this represents one proven approach, the broader experimental data suggest that a variety of alternative detailing strategies may also be engineered to achieve comparable performance. In fact, the other experimental programs shown in Figure 10 did not incorporate details explicitly intended to improve ductility. However, design and detailing considerations in these specimens appear to have incidentally provided sufficient ductility. It is important to recognize these details when interpreting the data shown in Figure 10 for two reasons: (1) to avoid overgeneralizing the results to situations where such details may not be present and (2) to identify and take advantage of beneficial attributes. In this context, the various test programs that demonstrated high ductility incorporated one or more of the following features (see individual program references for details): smooth bars either bonded to or debonded from the concrete, weld details designed to develop the strength of the attached column, and sufficient embedment within the concrete to develop the strength of the anchors. While such details may not always be present in nonseismic bases, they are nevertheless standard and straightforward to incorporate. This is encouraging, suggesting that even without expensive detailing, ductile performance (and weak-base design) is well within reach. Research is needed to definitively establish detailing practices, as well as material and anchor specifications that are able to achieve such ductility.

SUMMARY, CONCLUSIONS, AND REMAINING KNOWLEDGE GAPS

Column base connections are essential to the performance of steel structures, serving as the critical interface between the steel superstructure and the supporting foundation. Despite their ubiquity and structural importance, base connections have historically received limited research attention relative to other structural components. However, the past two decades have seen a significant increase in experimental, analytical, and computational studies, resulting in a more comprehensive understanding of base connection behavior and improved design guidance. This paper has

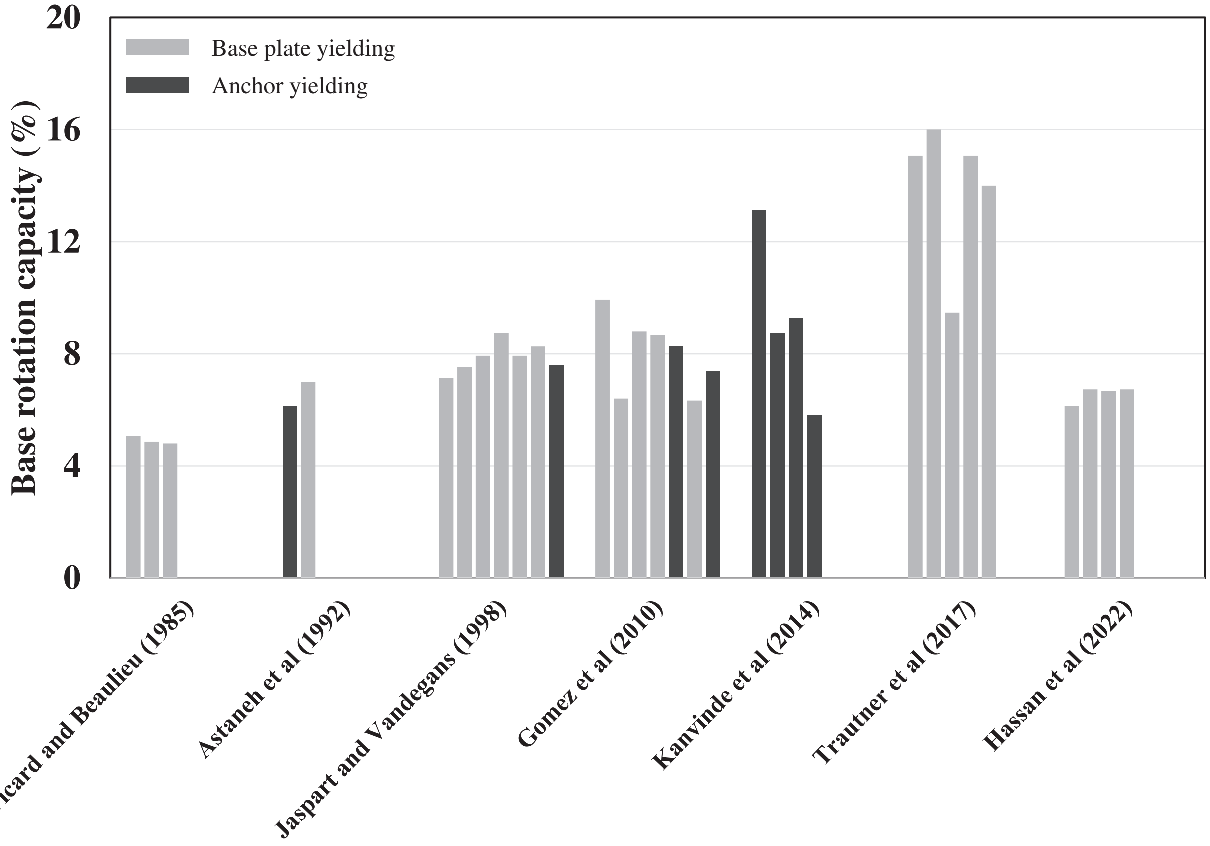


Fig. 10. Base rotation capacity of base connections in various test programs.

reviewed these developments, with emphasis on strength models, seismic performance, modeling approaches, and emerging design philosophies.

Significant advancements have been made in understanding and designing both exposed and embedded base connections, including their internal force distributions and governing limit states. For exposed base plates, widely used strength models such as the Drake and Elkin method continue to perform well, particularly in cases where anchor rod yielding governs. However, limitations in these simplified methods, particularly for complex geometries, have motivated the adoption of more sophisticated tools, such as finite element and component-based models, which can better capture complex response, including multidirectional loading. Embedded base connections, once underexplored, have received increased attention in recent years. New research has yielded reliable strength models and clarified load paths, particularly for deeply embedded configurations. These findings are now reflected in the 3rd Edition of AISC Design Guide 1, which also introduces tools to support practical design. Notably, incidental embedment in shallowly embedded connections has been shown to influence system-level behavior, highlighting the need to consider such effects in performance assessments.

Advances in simulation methods now allow for the accurate representation of base connection stiffness and inelasticity in structural analyses. Rotational spring models provide a simple yet effective approach for elastic design, especially when augmented to account for axial load effects. More detailed line-element-based models can simulate complex behaviors under seismic loading, including axial–moment interaction and uplift effects. The development and dissemination of validated modeling tools—now available through AISC resources—represents a key step toward the broader integration of connection behavior into global frame analyses.

In the context of seismic design, two primary design strategies are prevalent: the *strong-base* approach, which capacity-designs the connection to remain elastic, and the *weak-base* approach, which permits and controls inelastic deformation at the base. Research has shown that both strategies can achieve acceptable seismic performance, provided that specific criteria related to shear resistance, rotational capacity, and column strength are met. Moreover, the ductility demands of weak-base connections are substantial but achievable through rational detailing, evidenced by test programs that demonstrate impressive deformation capacities, even in connections not explicitly designed for ductility.

Despite recent advances, several important knowledge gaps remain. Research on base connections in braced frames is particularly limited, leading to significant uncertainties regarding internal force distributions and deformation capacities. This deficiency hampers the development of robust design methodologies, especially for seismic applications where leveraging the ductility of base connections to implement weak-base strategies remains a priority. In addition, while substantial progress has been made in characterizing the behavior of individual connections, the broader implications of base connection stiffness and strength on system-level seismic performance require further exploration. Another critical area that remains virtually unexplored is the interaction between the base connection, the supporting foundation, and the underlying soil. Key gaps persist in understanding how different foundation types—such as mat foundations, pile caps, individual pedestals, or configurations with grade beams—affect the load path from the column base into the ground. Equally lacking is a unified design methodology that integrates the behavior of the entire base-connection–foundation–soil system. Current practice tends to treat these components in isolation, potentially overlooking important interactions that influence global structural performance. Finally, as design for repairability and functional recovery gains more recognition and adoption in standards, addressing it will be essential for advancing toward more holistic and resilient design approaches.

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