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AN EXPLICIT MODEL FOR EXPOSED COLUMN BASE CONNECTIONS AND ITS PARAMETER SENSITIVITY

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Abstract. *Exposed column bases are the connection type most often employed in low to mid-rise steel moment resisting frames. Design typically follows idealized conditions for their boundaries, i.e. either pinned or fixed. In truth, the bases' behavior falls between those two cases and, depending on their design, can have important system-level seismic performance implications. The main objective of this paper is to present the details of a recently developed modeling approach for exposed column bases and help guide its use. It will start by briefly reviewing the chief factors involved in the hysteretic response of these connections. After, an explicit mechanics-based model is presented in which each component of the base is individually simulated. Sensitivity studies on features such as material modeling parameters as well element discretization levels are then conducted to assess the model's performance. Recommendations are made on its effective use, as are remarks pertaining to its limitations.*

1 INTRODUCTION

The ubiquity of exposed column bases (XCBs) in steel moment resisting frames (MRFs) means that it has long been the object of study – *cf.* [1] for a thorough review of the subject. Design assumptions are often considered in idealized conditions, *i.e.* pinned or fixed. Pinned supports generally lead to conservative column member sizes ([2]). Fixed XCBs are designed in seismic situations to be elastic in accordance with the capacity of the column including overstrength effects ([3–5]), which typically results in large base plate thicknesses and anchor rod sizes. Notable attempts at classifying the behavior and failure modes of XCB connection are made in [6, 7]. The fixed design principle leads to one of two principal failure modes: weak column/strong base. Although it can be stated that XCBs designed for fixed conditions mobilize their intended design strength, they are prone to brittle fracture if welds are not properly executed ([8]). Additionally, greater than expected overstrength can induce limited yielding of the base components thereby affecting their nonlinear response, the consequences of which are as yet to be fully understood ([2]). Conversely, in the weak base/strong column case, failures could be expected in the underlying grout or concrete foundation (crushing), or the steel components of the XCB, *i.e.* the base plate, the anchor rods or eventual shear lugs. Design standards that allow for this failure mode are less pervasive, with only the Japanese ([9]) and more recently the American standards ([3]) allowing for the promotion of anchor rod yielding.

Accurate modeling of structural responses to earthquake loading is a delicate process where the need to dissipate seismic energy often motivates exploiting the nonlinear behavior of its components. Inescapable in this approach is the confluence of geometric and material nonlinearities whose synergy can lead to nontrivial system level performance and result in unexpected failure modes naturally overlooked during the design process. A contextual example in this regard is the deceptively simple issue of varying the elastic stiffness at supports of steel MRFs, which not only impacts significantly story drift profiles but also effects the formation hierarchy of plastic hinges throughout a building [2, 10, 11]. It necessarily follows that more intricate features such as component deterioration can also have a considerable global impact. In mid-to-low rise MRFs several experimental and computer simulation studies show that first story open-section columns complying to design code provisions for seismic compactness (e.g. [4]) can be subject to excessive deformation due to local buckling, lateral torsional buckling and axial shortening which at the moment can only be reliably modeled through sophisticated finite element representations ([12–16]). Shifting governing dissipation processes to more dependable mechanisms is a strategy frequently employed to avoid modeling complexities and increase response reliability. In cases where extensive first-story column yielding is expected to assure system performance, the aforementioned issues can be mitigated by transferring yielding from the column element to the supports ([17]). Exploring this option, however, requires detailed knowledge of the hysteretic response at the column base and motivates the current study.

The cyclic behavior of XCBs emerges from the interaction of its several components and the external loading. Extensive experimental data exist that characterize their behavior in order to assess the adequacy of modeling techniques – *c.f. e.g.* [8, 18–21]. Exposed column bases designed for weak column/strong base situations have their dominant nonlinear behavior in the form of plastic hinges in the column and thus their moment-rotation relationship can be modeled with established methods such as the modified Ibarra-Medina-Krawinkler (IMK) model even in the post-peak response ([22, 23]). Weak base/strong column cases, however, have added complexity as there are more intervening components. One of the chief challenges is capturing the slip behavior between the anchor rods and the base plate when anchor rod yielding takes place and the accompanying contact problem between the base plate and the foundation. In the presence of axial load, slipping and subsequent rocking of the base plate induces pinching behavior in the moment-rotation curve of the connection. Prominent efforts in modeling this phenomenon are given in [24] whose approach centers around a modification of the IMK model. This model, however, requires a large number of empirical parameters and can only account for constant axial loading in the column.

A different approach is proposed by [25] where the XCB is modeled explicitly, *i.e.* each individual component of the connection is part of an overall 2D frame structural model. This pathway intrinsically captures the effects of variable axial load as well as the nonlinear interaction between the components. The benefit of having a mechanics-based model is considered to outweigh the added computational cost.

The XCB modeling approach presented in this work builds on the explicit approach by integrating more refined material laws and considers previously disregarded details that significantly affect the XCB hysteretic behavior (*e.g.* the presence of leveling nuts – *c.f.* [20]). Validation and applications of this technique can be found in other publications by the authors ([17]). The main objective of this paper is to study the sensitivity of the parameters in the proposed mechanics-based model. The susceptibility of XCB response to parameter perturbations is of interest in identifying its governing factors thereby guiding potential alternative design criteria. Sensitivity analyses are achieved by establishing a systematic methodology similar to [11] in its reliability assessment, but with different metrics pertaining to the moment-rotation hysteresis of the explicit model. The analyses are solely focused on XCB designs that privilege anchor yielding.

2 METHODOLOGY

2.1 Identification of relevant behavior parameters

Assessing the performance of an XCB requires detailed knowledge of its components. Fig. 1 shows a typical open cross-section XCB connection and provides an at a glance overview of its constituents and the relevant nomenclature used throughout this paper.

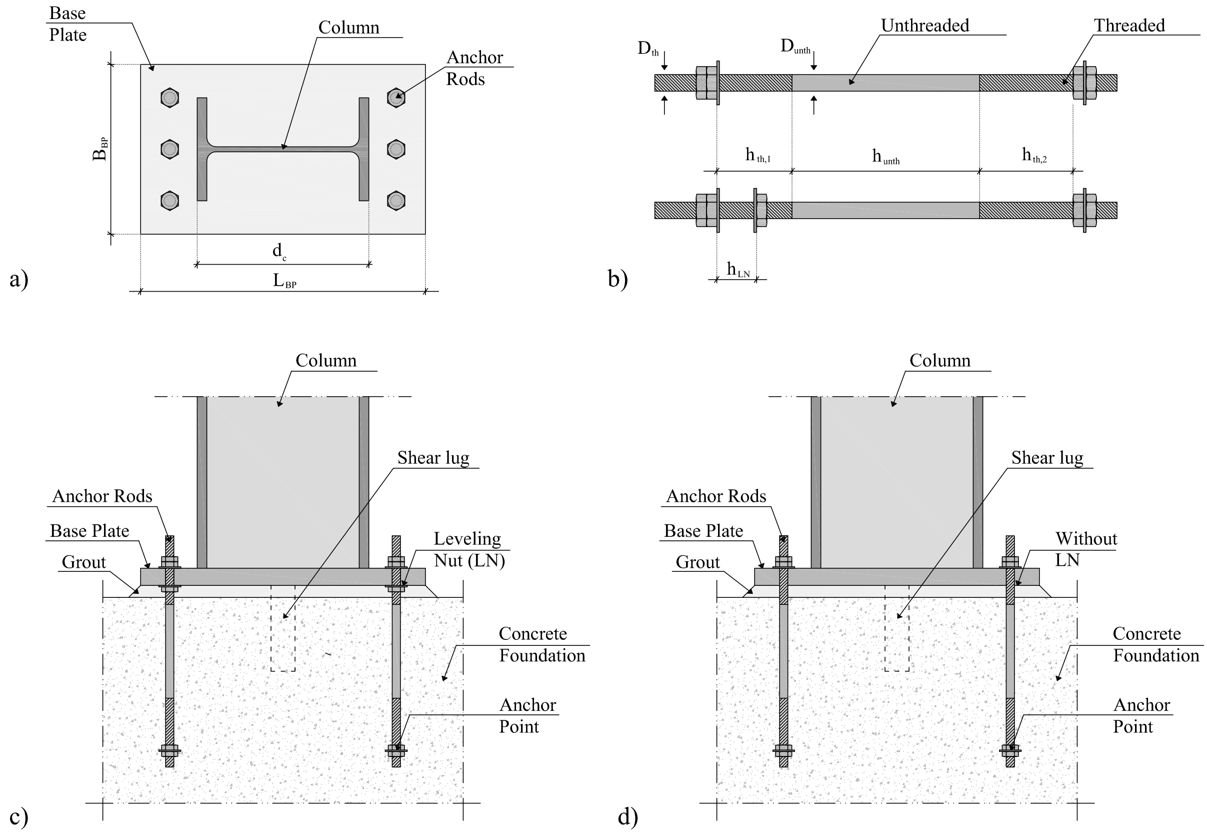


Figure 1. Exposed column base sketch: a) Plan view; b) Anchor rods with/without leveling nut; c) Elevation with leveling nut; d) Elevation without leveling nut

Although the current focus is on the XCB cyclic response, it is useful to reason on its components as a function of their failure modes. The XCB components and corresponding failure modes are the following:

1. Foundation - failure mode can be either grout or concrete crushing due to bearing of the column in axial and/or bending or bearing of the shear lug in shear loading;
2. Column – failure modes include weld fracture to the base plate and excessive local deformation due to nonlinear geometric effects and subsequent fracture;
3. Base plate - the failure mode is fracture due to bending and can take place either in the tension side next to the rod or on the compression by bearing on the foundation;
4. Anchor rod – failure mode consists of fracture due to excessive straining in bending and/or axial and/or shear loading;
5. Shear lug – failure mode consists of fracture of the weld of the lug to the base plate.

From the above list, characteristics like ductile post-peak response can be said to be dominated by nonlinear geometric effects on the column and nonlinear material behavior of the foundation. Other failure modes do not have a significant post peak strength as they are due to fracture of the steel material which, due to strain concentration over a limited space (*e.g.* necking) is challenging to detect at the component level – *c.f.* the classification of rod fracture as brittle in [1]. Prior to peak strength of the XCB connection, hysteresis is controlled by nonlinear material behavior of the components and their interaction with external loading.

2.2 Modeling assumptions, the explicit approach and validation cases

The modeling approach presented hereafter was developed with a focus on the study of anchor rod yielding cases. Although it is deemed sufficiently general to incorporate nonlinear effects of other components, validations beyond anchor yielding and elastic base situations are still needed. Therefore, the following assumptions are to be considered:

1. Foundation stays elastic and is adequately represented by a discrete Winkler spring approach;
2. Shear loading is fully transferred to the foundation by friction or through a shear lug designed in such a way that it is not the weakest link;
3. Bonding between rod and concrete foundation does not play a significant role in the stiffness of the connection – c.f. [19, 21, 26]. More precisely, the rod's stiffness is considered to be accurately represented by the rod length between the top of the base plate and the anchor point;
4. Base plate presents limited yielding but does not govern the hysteresis;
5. The base plate area within the contours of the column is sufficiently stiff to be considered as rigid;
6. Accurate steel material parameters are available or can be derived from existing data;
7. Accurate geometric properties such as threaded and unthreaded length and diameters of rods are known, as well as the position of an eventual leveling nut;

The explicit approach entails a detailed description of the component in a 2D frame structural model. To that effect, the finite element software OpenSEES ([27]) is used for its implementation. Figure 2 shows an overview of the modeling features with and without the presence of leveling nuts. For the column dominated hysteresis, a zero-length element with the IMK material model is used at the interface of the column and the XCB. The parameters of this model are based on recent work regarding the hysteretic behavior of steel wide-flange columns by the third author ([28]).

With respect to the base plate modeling, rigid elastic beam-column elements are used within the column contours. Outside the column contours the base plate is modeled by fiber-section displacement-based nonlinear elements with an in-house implementation of the Voce-Chaboche (VC) material model ([29, 30]). These elements are modeled by single segments between Winkler spring nodes with 5 integration points. Base plate elements rest upon elastic trusses that act as discrete Winkler springs. Contact between the base plate and foundation is taken into account by assigning an elastic-no-tension (ENT) material model to the trusses. The positive axial stiffness of the foundation truss elements themselves are computed following the assumption of a rectangular rigid plate in an infinite elastic medium per [31].

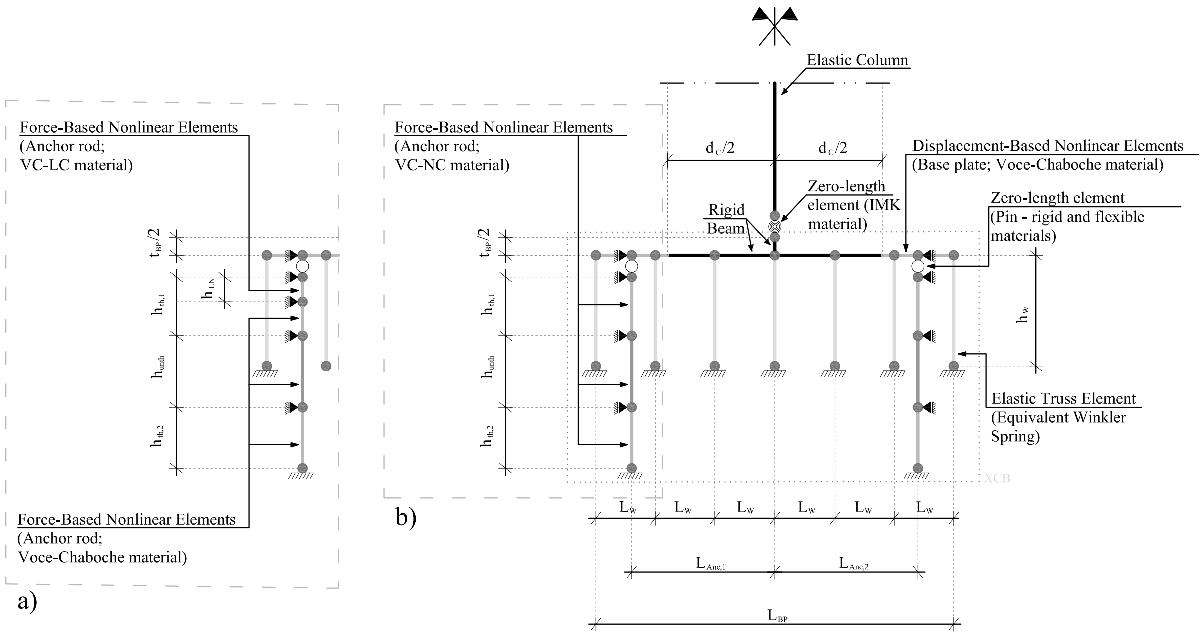


Figure 2. OpenSEES XCB modeling details: a) anchor rod with leveling nut; b) anchor rod without leveling nut

Anchor rods are modeled by force-based elements with 5 integration points and with circular fiber-sections of different cross-sectional areas and material models, depending on their location. Two different composite material models are used depending on the presence of leveling nuts. A schematic representation of the two models is given on Fig. 3. The first among the two is designated the Voce-Chaboche No-Compression material (VC-NC) and is the result of combining two materials in series: 1) the standard VC model and 2) an elastic-no-compression (ENC), rigid in tension. The purpose of this material is to simulate slip between the base plate and the anchor rods by having, in practical terms, zero stiffness when in compression which allows free movement at the anchor position. The second material is designated Voce-Chaboche Limited-Contact (VC-LC). It is comprised of the VC-NC set up in parallel with an ENT material (rigid in compression strains). The behavior of the VC-LC is similar to the VC-NC with the exception that it is practically rigid in compression. The aim of this material is both to model slip and to capture contact on the leveling nut solely within the leveling nut length. The rigid nature of the material under compression strains prompts the engagement of the VC hysteresis in the underlying anchor rod elements.

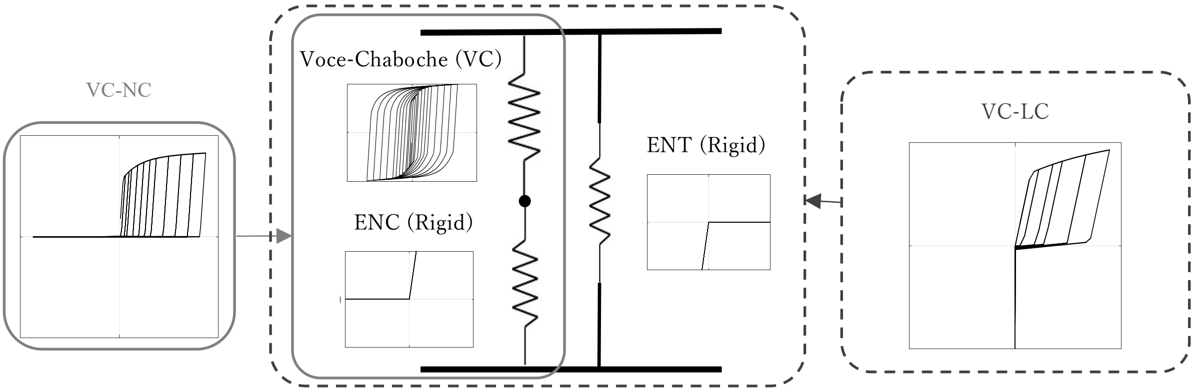


Figure 3. Anchor rod material representation

Another noteworthy modeling detail of this implementation is the use of limited damping on some of the elements of the XCB. This choice stems from the need to have rapidly converging nonlinear simulations. It was found that solving an XCB problem in the form of a dynamic analysis with negligible damping significantly improves convergence issues that are the product of large stiffness differences within the model. Elements within the XCB should, nevertheless, be checked to ensure negligible damping forces throughout the analysis.

Some validation cases of this approach can be found in [17]. Fig. 4 shows two examples from that publication that illustrate the performance of the explicit model in modeling two of the most complex features of XCB response: 1) variable axial load dependency, as shown by the flag-shaped hysteresis influenced by variable P-Delta effects; and 2) effect of leveling nut detailing, as shown by the increasingly wider body of the flag-shaped hysteresis.

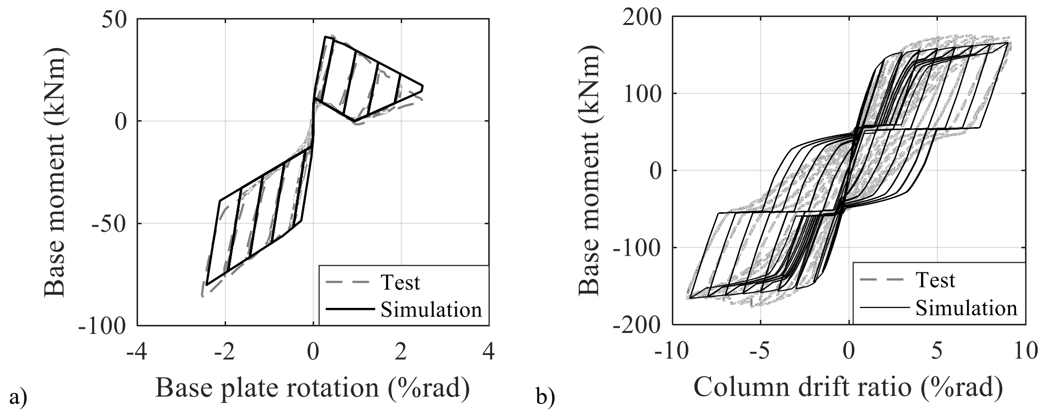


Figure 4. Comparison of moment-rotation response between the explicit approach and test data: (a) data from [18] - specimen 'S-Var'; and (b) data from [19] - specimen 5. Figure adapted from [17].

2.3 Analysis metrics and sensitivity of parameters

The adequacy of the explicit approach having been established it is now left to address the issue of the sensitivity of the response to the model parameters. Foremost, an analysis metric should be established in order to unambiguously define the performance of the XCB explicit model. Eqs. 1-4 define metrics based on the deviation of the accumulated moment-rotation response between a reference XCB simulation and another with a perturbated parameter set α. Eq. 1 defines an accumulated rotation quantity that is the basis for the integrating the deviations and results in the definition of the sensitivity metric φ in Eq. 2. Eq. 3 defines a normalized quantify $\bar{\varphi}$ that is better suited for comparing different models. Eq. 4 defines the change in $\bar{\varphi}$ per unit variation of factor α from the reference case.

$$\theta_{accum} = \int_0^t \left|\dot{\theta}\right| d\tau \tag{1}$$

$$\varphi = \frac{\int_0^{\theta_{accum}} \left(M_\alpha(\bar{\theta}) - M_{ref}(\bar{\theta})\right)^2 d\bar{\theta}}{\int_0^{\theta_{accum}} d\bar{\theta}} \tag{2}$$

$$\bar{\varphi} = \sqrt{\varphi / \frac{\int_0^{\theta_{accum}} \left(M_{ref}(\bar{\theta})\right)^2 d\bar{\theta}}{\int_0^{\theta_{accum}} d\bar{\theta}}} \tag{3}$$

$$\xi = \bar{\varphi}/\Delta\alpha \tag{4}$$

This work will analyze the effects of 8 variables by performing perturbations on the quantities - many with a factor α. The variables and corresponding factors are defined as follows:

1. Number of Winkler springs ($n_{Winkler}$);
2. Stiffness of Winkler springs – Eq. 5;

$$k_{Winkler,i,\alpha} = \alpha_{Winkler} k_{Winkler,i,ref} \tag{5}$$

3. Ratio of threaded over unthreaded area of anchor rods. The threaded area is kept constant while the unthreaded area is changed – Eq. 6;

$$A_{unth,\alpha} = \alpha_{unth} A_{unth,ref} \tag{6}$$

4. Threaded length over total length – Eq. 7. Total length is kept constant while threaded length is changed;

$$h_{th,i,\alpha} = \alpha_{h_{th}} h_{th,i,ref} \tag{7}$$

5. Leveling nut threaded length with respect to the threaded length – Eq. 8;

$$h_{LN,\alpha} = \alpha_{\mathrm{LN}} h_{\mathrm{LN},ref} \tag{8}$$

6. Axial load (P) – Eq. 9;

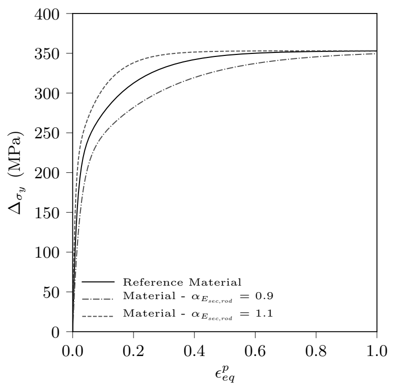
$$P_{\alpha} = \alpha_{\mathrm{P}} P_{ref} \tag{9}$$

7. Plastic secant modulus in monotonic loading of the rod material at a reference strain as simulated by the VC model. A secant plastic modulus (E_{sec}) is defined here as the ratio of the hardening stress ($\Delta\sigma_{y,0}$) to a reference equivalent plastic strain (ε_{eq}^{p}). To achieve this effect, new parameters are calculated such that the material saturates at the same values as the reference material and rates under isotropic and kinematic hardening are affect by the same proportionality factor. A variation about this reference stiffness is defined by Eq. 10. A reference equivalent plastic strain of 15% is used in this study. Fig. 5a show examples of a material responses to this kind of perturbations.

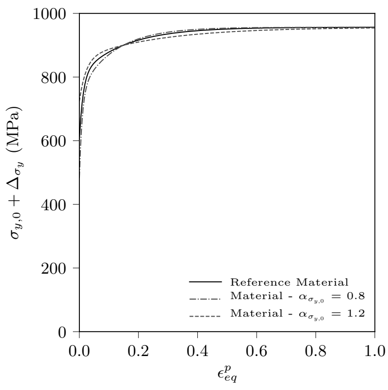
$$E_{sec,rod,\alpha} = \alpha_{\mathrm{E}_{sec,rod}} E_{sec,rod,ref} \tag{10}$$

8. Initial yield of the rod material ($\sigma_{y,0}$). Similarly, to the plastic secant stiffness, new material parameters are calculated such that variations according to Eq. 11 are made. Conditions are imposed such that the material: 1) saturates under monotonic loading at the same values of the original material; 2) passes through the same stress value at a reference equivalent plastic strain; 3) rates under isotropic and kinematic hardening are affect by the same proportionality factor; and 4) saturation values under isotropic and kinematic hardening are affect by another proportionality factor. Fig. 5b exemplifies this type of perturbation.

$$\sigma_{y,0,\alpha} = \alpha_{\sigma_{y,0}} \sigma_{y,0,ref} \tag{11}$$



a)



b)

Figure 5. Example of VC model response to perturbations on rod material from tests in [19] - specimen 5: a) secant stiffness; b) initial yield.

3 RESULTS AND DISCUSSION

The results of sensitivity analyses for two cases are presented in this section. The reference cases consist of simulation results that adequately follow the moment-rotation hysteresis reported in [32] (specimen Fix-Ab-N=0.1NyC) and [19] (specimen 5). An example of the model performance of the specimen 5 is shown in Fig. 4b. This test was chosen as it shows the effect of the leveling nut detail. As for specimen Fix-Ab-N=0.1NyC, it was chosen to conduct this analysis due to its clear anchor rod yielding behavior. The XCB was not only designed to promote anchor yielding but it also rests upon a steel foundation and is submitted to a constant axial load, which results in a transparent flag-shape hysteresis. For the underlying geometric and material characteristics of tests, the reader is referred to their respectively publications. The material properties used in the analyses for the VC model are derived using as a basis the methodology and parameters described in [33].

Tables 1 and 2 shows the parameter matrices and their corresponding results, according to the metrics defined in Eqs. 2-4, for specimen Fix-Ab-N=0.1NyC and specimen 5, respectively.

Table 1. Analyses factors and sensitivity metrics for specimen Fix-Ab-N=0.1NyC from [32].

Simulation Label	$n_{Winkler}$	$\alpha_{Winkler}$	$\alpha_{unth\_}$	$\alpha_{h_{th}}$	$\alpha_{LN\_}$	α_P	$\alpha_{E_{sec,rod}}$	$\alpha_{\sigma_{y,0}}$	φ	$\bar{\varphi}$(%)	ξ (%/.)
Reference	15	1.0	1.0	1.0	-	1.0	1.0	1.0	0.0e0	0.0	0
nW_7	7	1.0	1.0	1.0	-	1.0	1.0	1.0	1.0e08	1.3	-0.16
nW_51	51	1.0	1.0	1.0	-	1.0	1.0	1.0	1.7e08	1.7	0.05
aW_01	15	0.1	1.0	1.0	-	1.0	1.0	1.0	2.0e09	5.8	-6.44
aW_10	15	10.0	1.0	1.0	-	1.0	1.0	1.0	4.9e08	3.9	0.43
aAunth_095	15	1.0	0.95	1.0	-	1.0	1.0	1.0	4.0e09	8.2	-164.00
aAunth_12	15	1.0	1.2	1.0	-	1.0	1.0	1.0	3.8e11	80.2	401.00
aHth_08	15	1.0	1.0	0.8	-	1.0	1.0	1.0	1.7e07	0.5	-2.50
aHth_12	15	1.0	1.0	1.2	-	1.0	1.0	1.0	1.6e07	0.5	2.50
aP_08	15	1.0	1.0	1.0	-	0.8	1.0	1.0	1.3e10	14.5	-72.50
aP_12	15	1.0	1.0	1.0	-	1.2	1.0	1.0	4.7e10	28.3	141.50
aEsec_09	15	1.0	1.0	1.0	-	1.0	0.9	1.0	1.6e09	5.2	-52.00
aEsec_11	15	1.0	1.0	1.0	-	1.0	1.1	1.0	3.5e09	7.7	77.00
aSy_08	15	1.0	1.0	1.0	-	1.0	1.0	0.8	5.7e09	9.8	-49.00
aSy_12	15	1.0	1.0	1.0	-	1.0	1.0	1.2	5.5e10	30.4	152.00

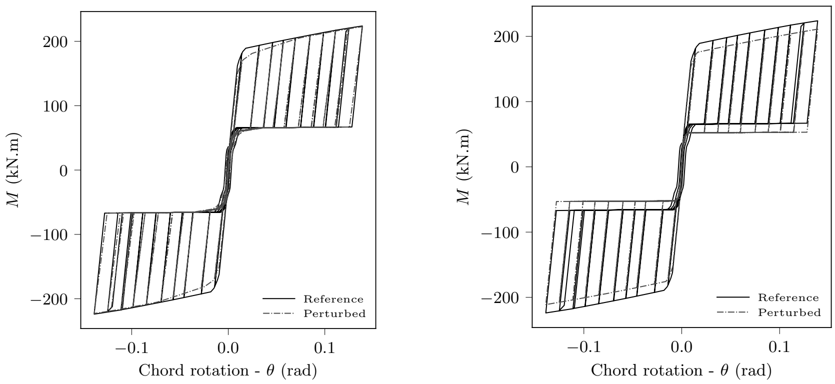
Table 2. Analyses factors and sensitivity metrics for specimen 5 from [19].

Simulation Label	$n_{Winkler}$	$\alpha_{Winkler}$	$\alpha_{unth\_}$	$\alpha_{h_{th}}$	$\alpha_{LN\_}$	α_P	$\alpha_{E_{sec,rod}}$	$\alpha_{\sigma_{y,0}}$	φ	$\bar{\varphi}$(%)	ξ (%/.)
Reference	15	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0e0	0.0	0.00
nW_7	7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5e08	1.9	-0.24
nW_51	51	1.0	1.0	1.0	1.0	1.0	1.0	1.0	8.6e07	1.4	0.04
aW_01	15	0.1	1.0	1.0	1.0	1.0	1.0	1.0	4.0e09	9.7	-10.78
aW_10	15	10.0	1.0	1.0	1.0	1.0	1.0	1.0	3.2e08	3.5	0.39
aAunth_086	15	1.0	0.86	1.0	1.0	1.0	1.0	1.0	2.5e10	24.2	-172.86
aAunth_12	15	1.0	1.2	1.0	1.0	1.0	1.0	1.0	8.9e09	14.5	72.50
aHth_08	15	1.0	1.0	0.8	1.0	1.0	1.0	1.0	2.8e08	2.6	-13.00
aHth_12	15	1.0	1.0	1.2	1.0	1.0	1.0	1.0	1.8e08	2.1	10.50
aLN_08	15	1.0	1.0	1.0	0.8	1.0	1.0	1.0	3.5e09	9.0	-45.00
aLN_12	15	1.0	1.0	1.0	1.2	1.0	1.0	1.0	4.5e09	10.2	51.00
aP_08	15	1.0	1.0	1.0	1.0	0.8	1.0	1.0	2.2e09	8.7	-43.50
aP_12	15	1.0	1.0	1.0	1.0	1.2	1.0	1.0	3.6e09	9.1	45.50
aEsec_09	15	1.0	1.0	1.0	1.0	1.0	0.9	1.0	6.6e08	3.4	-34.00
aEsec_11	15	1.0	1.0	1.0	1.0	1.0	1.1	1.0	9.3e08	4.0	40.00
aSy_08	15	1.0	1.0	1.0	1.0	1.0	1.0	0.8	1.0e10	13.5	-67.50
aSy_11	15	1.0	1.0	1.0	1.0	1.0	1.0	1.2	1.0e10	13.2	66.00

The normalized metric $\bar{\varphi}$ gives a sense of the magnitude of the deviation between the simulations. For a visual representation of this magnitude one refers to Fig. 6 where a few examples of moment-rotation hysteresis for specimen Fix-Ab-N=0.1NyC are given.

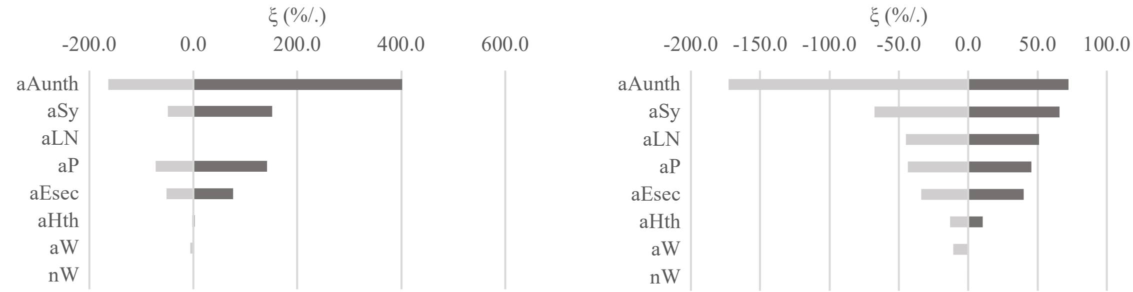
Consider, also, the tornado plot in Fig. 7 which shows the relative weight of each factor on the overall performance of the model with the sensitivity metric ξ. Recall that ξ, defined by Eq. 4, expresses the increase in $\bar{\varphi}$ per unit change in the factor under analysis. A negative value expresses the negative directional change in the factor's magnitude.

Some general remarks on the explicit approach can be made by observing the results from Tables 1 and 2, and Fig. 7. Firstly, the discretization level of the Winkler springs does not appear to substantially affect the model's hysteretic behavior. This is an important observation since the discretization level can carry with itself a high computational burden. Secondly, the stiffness of Winkler springs can have an order of magnitude imprecision at only a mild cost to the performance of the model. This observation seems to suggest that estimation of the subgrade modulus of the foundation, with simplifications such as the consideration of a rectangular plate on an infinite elastic medium, are sufficiently precise. It also stands to reason that limited foundation crushing would have an acceptable impact on the accuracy of the model and motivates the first assumption listed in section 2.2.



a) b)

Figure 6. Example of perturbations for specimen Fix-Ab-N=0.1NyC from [32]: a) simulation aW_01; b) simulation aP_08.



a) b)

Figure 7. Tornado plot for sensitivity factor ξ in Tables 1 and 2: a) specimen Fix-Ab-N=0.1NyC from [32]; b) specimen 5 from [19].

The ratio of unthreaded to threaded areas of the rod is among the most consequential factors in the performance of the XCB connection. This observation is supported by the relatively high values of $\bar{\varphi}$ in both specimens. The conspicuously high value of 80% for specimen Fix-Ab-N=0.1NyC is the product of shifting the main yielding mechanism from the rod to the column. This shift is responsible for a considerably different XCB hysteresis. Additionally, the lower bound on α_{unth} reflects the cases where the unthreaded area is approximately equal to the threaded one, *i.e.* at these values the rod would have the same cross-sectional area throughout its length. There are two important takeaways from this fact: the first, that differences as small as 5% in area can have that same impact as differences in an order of magnitude in foundation stiffness; the second, that there is a substantial difference in the products used in both tests considering the first observation. The anchors used in specimen Fix-Ab-N=0.1NyC are made in Japan and are produced in such a way that the yield ratio (the ratio between the yield and the ultimate stress) is smaller than the ratio between the threaded and the unthreaded area (α_{unth}) – *c.f.* [9]. The intention behind this rule is to increase rod ductility by assuring that the unthreaded area is engaged in the yielding process after some amount of hardening takes place in the threaded segments. As a consequence, plastic strains are not concentrated solely in the threaded parts but also spread to the unthreaded shank, leading to larger rod elongations. Adopting fabrication procedures that maximize α_{unth} help fulfill this condition for a wide range of materials and motivates the high values for the product in specimen Fix-Ab-N=0.1NyC. Parenthetically, despite having a larger yield strength material, and hence a lower yield ratio, the product used in specimen 5 has a much lower α_{unth}. The aforementioned facts underscore a need for carefully manufactured products not only because of their ductility but also for the influence that the area ratio has in the XCB hysteretic behavior.

With respect to threaded length of the rods, they do not appear to be of significant impact for the XCBs response histories. In contrast, the length assigned to the leveling nut appears to be considerably consequential for the hysteresis. The rationale behind this effect is that strains tend to be concentrated within this limited region, thereby significantly affecting elongation if its length changes. It should be noted that, because this metric is so sensitive, a seemingly unrelated variable, the base plate's thickness, can have an influence in the hysteresis not because of base plate yielding but because of its influence on the anchor rod's performance.

As for axial loading, it was expected that the hysteresis would be significantly impacted by this variable as it is suggested by numerous experimental observations – *c.f. e.g.* [1]. The numerical results of the explicit approach are in line with these conclusions and underline the fact that simulations that fully capture the axial load interaction within XCB connections, including variable axial load effects, should be used for system-wide computations as they significantly affect their hysteresis.

In the matter of the rod's material hardening properties, it can also be said they have considerable impact - comparable even with the axial load influence. The perturbations on its hardening rate, as expressed by the secant plastic modulus, is less consequential than variations on the initial yield stress of the material. The magnitude of the deviations in yield stress analyzed in this study (20%) are within what can be reasonably be expected in standard structural steels (*c.f. e.g.* [34]) and, as such, care should be taken to obtain products that closely resemble the material properties assumed in an XCB design which privileges anchor rod yielding.

Lastly, it should be noted from Tables 1 and 2 that factors were varied one at a time for each simulation. To be sure, the anchor rod's factors (*e.g.* cross-sectional area, threaded length, and hardening properties) are not mutually independent when it comes to affecting the response of an XCB connection that promotes anchor rod yielding. This fact introduces an added complexity to the sensitivity of XCBs for this design situation that is not analyzed in this work. Additionally, and as discussed in the introduction, there are an increasing number of arguments in favor of using designs that favor anchor rod yielding. Some of those arguments leverage the performance of the explicit approach outlined in this work to form system-level conclusions. One such example is that it reduces repairability costs associated with column axial shortening in low rise buildings ([17]). The present work, however, seems to suggest that those conclusions are, by extension, also potentially sensitive to anchor rod properties. Nevertheless, it can be stated that products that privilege consistency in their manufacture process are of paramount importance to the reliability of XCBs and system performance. Altogether, the opportunity to significantly reduce building reparation costs appears to justify higher fabrication standards, which assure modeling assumptions.

4 CONCLUSIONS

The work presented in this paper addressed the question of the performance of an explicit modeling approach to exposed column bases (XCBs) that could facilitate simulation-based engineering design of high-quality products to control earthquake-induced damage in steel structures. It introduced the approach's methodology and also addressed its limitations by categorically presenting its fundamental assumptions. It also rendered sensitivity metrics that quantify deviations on moment-rotation hysteresis from a reference study case. These metrics are then used to make judgments on the variables governing exposed column base behavior. The main conclusions from two case studies that promote anchor rod yielding, based on experimental results with and without the presence of leveling nuts, are the following:

1. The controlling variable is the ratio of threaded to unthreaded cross-sectional area of the anchor rod;
2. Material properties such as the hardening rate and the initial stress of the rod also significantly affect the hysteretic behavior of the XCB;
3. When present, the leveling nut length plays a role on the same order of magnitude as the rod's material properties;
4. The discretization level and subgrade stiffness of Winkler springs do not significantly affect cyclic response of the XCB.

It was also concluded that the relatively high sensitivity of XCBs designed to promote anchor rod yielding to the rod's characteristics suggests that strict manufacturing standards should be employed in order maintain the underlying modeling assumptions.

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