Hydraulic and Civil Engineering Technology VII
M. Yang et al. (Eds.)

doi:10.3233/ATDE220990

A Design Method of Effective Length Coefficient for Irregular Non-Sway Steel Frame Columns with Staggered Beams

Rong RONG [a], Haisheng LIANG [a,1], Shun FAN [a], Bowei WANG [b] and Feng ZHOU [b]

[a] *State Grid Shanghai Economic Research Institute, Shanghai 200002, China*
[b] *State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China*

Abstract. The indoor substation is a key hub in the urban power system. Due to the need to arrange large main transformers and high- and low-voltage electrical types of equipment in a small space, the structure is characterized by frame beams discontinuity, which in turn causes the specificity of the boundary condition at the ends of the steel frame columns, forming a special class of irregular steel frame column whose buckling performance and effective length coefficient design method need to be studied urgently. In this paper, the effects of the staggered frame beams on the buckling loads and effective length coefficients of irregular steel columns in non-sway frames are investigated numerically. Based on the numerical results obtained from this study, the design formulae to calculate the effective length coefficients for irregular non-sway steel frame columns with staggered beams in frames are proposed. The effective length coefficients of irregular steel frame columns predicted by using the proposed design formulae can accurately reflect the influence of the misalignment height of frame beams.

Keywords. Effective length coefficient, indoor substation, irregular frame column, staggered beams

1. Introduction

Electricity, communication, and transportation are all parts of the infrastructure system for the normal functioning of modern cities, where the normal operation of the electrical system is closely related to the survival and development of the city [1]. As a conversion hub of the power system, a substation needs to have the capacity to defend against danger and maintain stable daily operations [2]. The indoor substation is one of the basic types of substations, whose main transformer and high- & low-voltage electrical equipment are arranged indoors. As China's urbanization continues to advance and land space becomes increasingly scarce, indoor substation has become the best choice for the construction of substations in densely populated areas due to their relatively small footprint, convenient daily management or maintenance, and strong resistance to harsh weather [3].

[1] Haisheng Liang, Corresponding author, State Grid Shanghai Economic Research Institute, Shanghai 200002, China; E-mail: LiangHS1979@163.com.

Indoor substations are mostly two- & three-story steel frame structures, which are relatively simple types of structures. However, as electrical equipment has to be arranged, there are a large number of irregularities in the structure such as missing floor slabs, staggered beams and large span spaces. Based on the equilibrium method and displacement method, the stability of regular steel frame columns has been well studied [4,5]. For the regular steel frame column, the effective length coefficient is a transcendental equation about the linear stiffness ratio, which can be solved and fitted to the design equations by numerical calculation methods in the current design codes including GB50017-2017 [6] and AISC360-10 [7]. The current design equations of the effective length coefficients of steel frame columns are all based on ideal assumptions of the regular steel frame. However, there is a type of irregular steel frame column with staggered beams in 110kV~220kV level indoor substations in Shanghai China. To ensure the stability of the substation structure, the buckling performance and effective length coefficient design method of this irregular steel frame column are necessary to be studied.

In this paper, the effects of the staggered beam on effective length coefficients of irregular non-sway steel frame columns are numerically investigated by using the finite element (FE) package ABAQUS (version 2021) [8]. Based on the numerical results, the effective length coefficient design equations for irregular steel frame columns with staggered beams in frames without lateral shifts are finally proposed.

2. Irregular Steel Frame Columns in Indoor Substation with Staggered Beams

The indoor substations including the Shanghai Pudong Jichun 110kV substation and the Shanghai Zhusong 220kV substation have been carefully studied. It should be added that the frame structure can be divided into two kinds of frames: sway frame and non-sway frame, and according to the survey results, this paper focuses on the non-sway frame. The schematic diagram of the irregular steel frame column with the staggered beam is shown in figure 1. The approximate range of the main structural parameters in the indoor substation is shown in table 1. The mechanical property parameters of the structural steel commonly used in the indoor substation frame could be taken as follows: the modulus of elasticity (E) equals 2.06×10^5 MPa; the Poisson's ratio (ν) equals 0.3; the standard value of yield stress (f_y) is 235 Mpa.

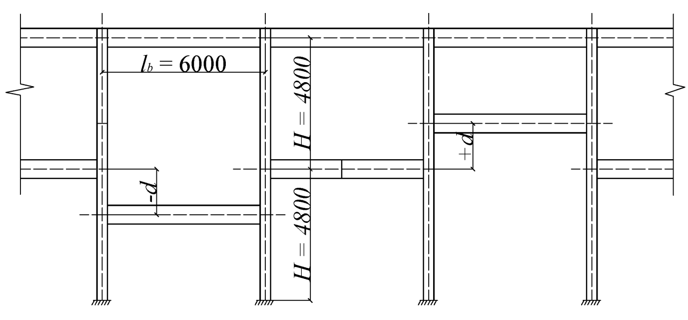


Figure 1. Schematic diagram of irregular steel frame column with staggered beams in indoor substations.

Table 1. Parameters of the indoor substation irregular steel frame with staggered beams.

Symbolic	Physical Quantity	Value
l_{bi}	The length of the frame beam; taken "$l_{bi}/2$" in the simplified model	6000mm
K	Linear stiffness ratio	0.5 ~ 4.0
H	Frame column height (based on the height of the frame column structure without staggered beams)	4800mm
d	Staggered space (Details in Figure 1)	-2400mm ~ 2400mm

The definitions of the symbols in table 1 are shown in figure 1 which also shows two cases of staggered space (d), greater than 0 and less than 0. With reference to the indoor substation projects, the beam and column sections considered in this study are all I-sections, and the dimensional parameters are approximately shown in table 2. The linear stiffness ratio K is an important parameter in the stability of steel frame column, which is defined as follows:

$$K = \frac{\sum I_b l_b}{\sum I_c l_c} \tag{1}$$

where "I_b" and "I_c" represent the moment of inertia of the beam and column section, respectively; "l_b" and "l_c" are the actual lengths of the beam and column, respectively.

A total of 49 different staggered spaces ranging from -2400mm to 2400mm with an increment of 100mm and 7 different linear stiffness ratios (K) were considered. Each linear stiffness ratio corresponds to four different sets of beam and column section combinations, as shown in table 2, where h, b, t_f and t_w stand for section height, flange width, flange thickness and web thickness, respectively.

Table 2. Section geometry parameters of frame beam and frame column.

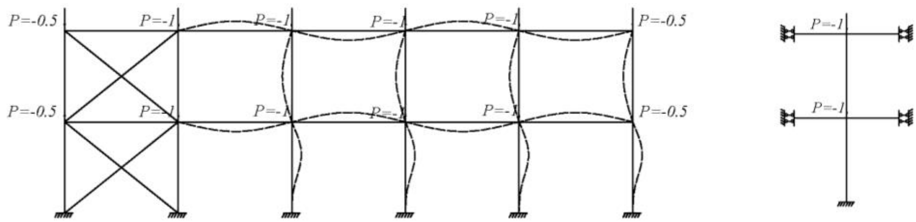
Linear stiffness ratio	Column section parameters $h \times b \times t_f \times t_w$ (mm)	Beam section parameters $h \times b \times t_f \times t_w$ (mm)	Linear stiffness ratio	Column section parameters $h \times b \times t_f \times t_w$ (mm)	Beam section parameters $h \times b \times t_f \times t_w$ (mm)
4.0	400×400×16×10	700×620×16×10	3.2	400×400×16×10	640×600×16×10
	350×350×14×14	600×565×14×14		350×350×14×14	550×545×14×14
	300×300×12×12	510×495×12×12		300×300×12×12	480×445×12×12
	200×200×8×6	340×330×8×6		200×200×8×6	320×300×8×6
2.0	400×400×16×10	600×415×16×10	1.6	400×400×16×10	550×400×16×10
	350×350×14×14	500×400×14×14		350×350×14×14	450×410×14×14
	300×300×12×12	405×400×12×12		300×300×12×12	380×365×12×12
	200×200×8×6	285×245×8×6		200×200×8×6	260×230×8×6
1.0	400×400×16×10	500×300×16×10	0.8	400×400×16×10	450×300×16×10
	350×350×14×14	400×320×14×14		350×350×14×14	350×350×14×14
	300×300×12×12	350×260×12×12		300×300×12×12	320×255×12×12
	200×200×8×6	220×200×8×6		200×200×8×6	200×200×8×6
0.5	400×400×16×10	400×235×16×10			
	350×350×14×14	300×300×14×14			
	300×300×12×12	285×200×12×12			
	200×200×8×6	180×155×8×6			

3. Numerical Investigation on Irregular Non-sway Steel Frame Columns with Staggered Beams

The finite element models (FEMs) for the buckling performance of the irregular frame columns with staggered beams are finely established by the software ABAQUS in this study. The effects of staggered beams on the buckling loads and effective length coefficients of irregular frame columns have been carefully studied.

3.1. Simplification of the Indoor Substation Steel Frame Structure FEM

To illuminate the steel frame column stability performance, the steel frame structures could be divided into two cases according to the current design codes, namely, sway and non-sway frames. Referring to the indoor substation projects in Shanghai China, a non-sway steel frame FEM is established by finite element software ABAQUS. To facilitate the study of the buckling performance of the indoor substation steel frame columns and parameter influence, the whole indoor substation steel frame FEMs without staggered beams are firstly established and simplified, as shown in figure 2.



(a). Five-bay non-sway frame FEM. **(b).** **S**implified frame FEM.

Figure 2. Whole indoor substation steel non-sway frame FEMs and simplified FEMs.

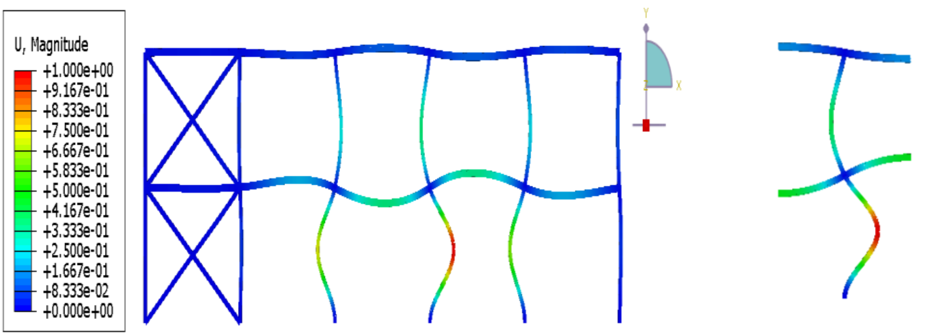
Based on the numerical results, the eigenvalue corresponding to the first-order buckling mode is selected as the critical buckling load, and the effective length coefficient of the steel frame column is calculated according to the Eulerian deformation formula (equation (2)). The applicability and validity of the simplified FEM were investigated by comparing the first-order flexural mode of the frame column and its corresponding effective length coefficient obtained from the whole indoor substation frame FEMs with those obtained from the simplified FEMs.

$$\mu = \sqrt{\frac{\pi^2 EI}{P_{cr} l^2}} \tag{2}$$

The line element, named “B21” was used to simulate the beam and column in the whole and simplified indoor substation steel frame FEMs. The structural dimensions and section parameters in the FEMs are shown in table 1 and table 2. Based on the mesh size sensitivity analysis, the size of the line element in this study is taken as 0.1 times the length of the member. The elastic linear regressive buckling analysis with a subspace iterative algorithm was used in both whole and simplified indoor substation frame FEMs. The number of eigenvalues is set to 3. On the basis of the deflection curve morphology of the frame structure after buckling, the boundary conditions of the free ends of the beam in the simplified indoor substation frame FEM are decided and shown in figure 2. For two-story non-sway frames, the rotational displacement and horizontal displacement are restricted at the free ends of the frame beams; for two-story sway frames, only the vertical displacement is restricted at the free ends of the frame beams. In the whole FEMs, a unity y-vertical compressive load is applied at the top of each central column, and a half unity y-vertical compressive load is applied at the side columns; in the simplified FEMs, a unity y-vertical load is applied at the top of each column, as shown in figure 2.

3.2. Verification of the Indoor Substation Steel Frame Structure FEM

The first-order buckling mode of the whole indoor substation steel frame FEM without lateral displacement is compared with the one of the simplified FEM, as shown in figure 3. The buckling shape of the middle column in the whole non-sway frame FEM is quite similar to the one in the simplified FEM. A comparison of the calculated effective length coefficients corresponding to the first-order buckling modes of the frame columns is made between the five-span whole indoor substation non-sway frame and the simplified FEMs, as shown in table 3. The average values (AVGs) in table 3 are the average values of the effective length coefficients obtained for the four sets of beam and column section combinations corresponding to each linear stiffness ratio K. The small value of the standard deviation (SD) indicates that the dispersion of the effective length coefficient obtained for the four sets of section combinations is small, implying that the linear stiffness ratio K is the main influence factor on the effective length coefficient of the steel frame column. The errors in table 3 are the relative small errors of the simplified frame FEMs to the five-span whole FEMs. Therefore, the simplified steel frame FEMs can effectively simulate the buckling performance and effective length coefficients of the frame columns in the whole indoor substation steel non-sway frame FEMs.



(a). Five-bay non-sway frame FEM. **(b).**Simplified frame FEM.

Figure 3. Comparison of the first buckling mode displacement clouds of frame columns between the five-bay whole non-sway steel frame and simplified FEMs.

Table 3. Section geometry parameters of frame beam and frame column.

Linear stiffness ratio	Simplified model(μ_1)		Five-span model(μ_0)		Error ($\frac{\mu_1-\mu_0}{\mu_0}\times 100\%$)
	AVG[a]	SD[b]	AVG[a]	SD[b]	
4.0	0.573	0.0217	0.570	0.0223	0.63%
3.2	0.579	0.0214	0.575	0.0219	0.80%
2.0	0.595	0.0205	0.588	0.0211	1.15%
1.6	0.604	0.0201	0.596	0.0206	1.30%
1.0	0.625	0.0184	0.616	0.0191	1.52%
0.8	0.636	0.0183	0.626	0.0189	1.57%
0.5	0.658	0.0175	0.648	0.0182	1.53%

[a]"AVG" is the average value.
[b]"SD" is the standard deviation.

3.3. Calibration of Simplified Steel Frame FEM

The buckling performance and effective length coefficients of steel columns in indoor substation non-sway steel frame with linear stiffness ratios K ranging from 0.5 to 4.0 could be well simulated by using the simplified steel frame FEMs, as mentioned in section 3.2. To further check the accuracy of the simplified steel frame FEMs, in this Section a kind of simple classical beam-column frame FEM is established. By changing the material modulus of the frame beam and the boundary condition of the free end of the frame beam, three classical boundary cases of frame column are simulated, namely hinged at both ends, fixed at both ends and fixed at one end and free at the other, as shown in figure 4. By comparing the numerical effective length coefficients of the frame columns with the theoretical values, the validity of the simplified frame FEM is checked.

In the simplified beam-column frame FEM, the frame column height is 4800 mm and the frame beam length is 3000 mm. The modelling approach is the same as the one considered in section 3.1.

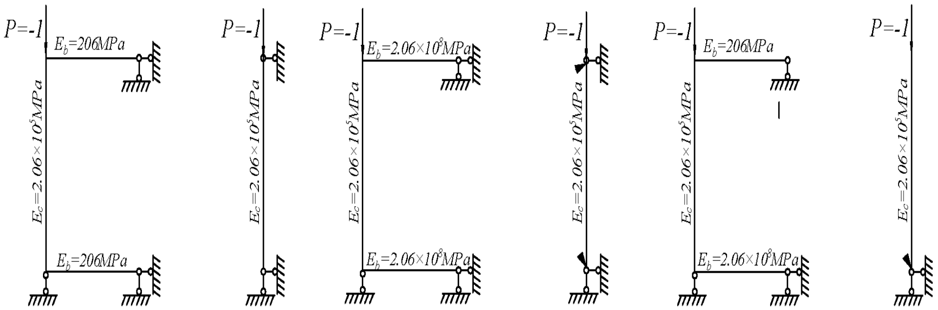
In the simplified beam-column frame FEM, boundary conditions and applied loads are shown in figure 4(a)~figure 4(c). The vertical displacement is restricted at the bottom of the frame column. To simulate a fixed boundary condition at the end, the connected beam material modulus of elasticity (E_b) is taken as 1000 times that of the column (E_c), and the displacements of the remote end of the beam are restricted. To simulate a hinged boundary condition at the end, the beam material modulus of elasticity (E_b) is taken as 0.001 times that of the column (E_c), and the displacements of the remote end of the beam are restricted. To simulate a free boundary condition at the end, the modulus of elasticity of the beam (E_b) connected to the end of the column is taken as 0.001 times that of the column (E_c), and the vertical displacement of the remote end of the beam is restricted only. A concentrated unity y-directional compressive load is applied at the top of the column.

The first-order buckling modes of the frame columns for the three types of boundary conditions are shown in figure 4(d)~figure 4(f). The numerical effective length coefficient is recorded as μ_1; the theoretical value is recorded as μ_0. The relative error is calculated as follows.

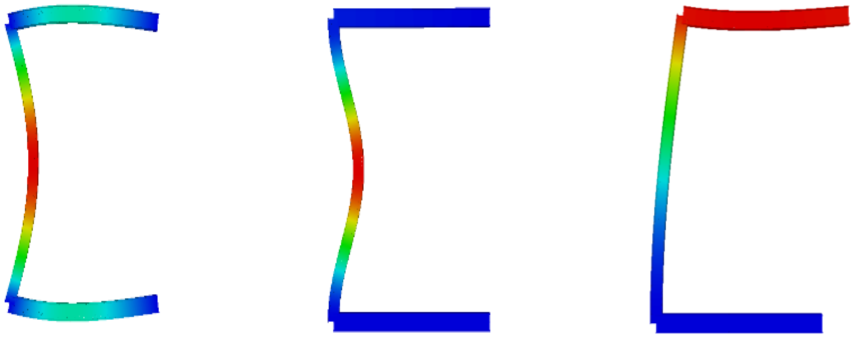
$$f_{error} = \frac{\mu_1 - \mu_0}{\mu_0} \times 100\% \tag{3}$$

where, when both ends of the column are hinged, μ_0 equals 1.0; when both ends are fixed, μ_0 equals 0.5; when one end is fixed and the other is free, μ_0 equals 2.0.

The numerical effective length coefficients of the simplified classical beam-column frame FEMs together with the theoretical values are shown in figure 5, where the numerical values are the average values of the effective length coefficients obtained for the four sets of section combinations in table 2. From figure 5, it can be concluded that the numerical effective length coefficients match well with the theoretical values. The maximum relative error is 2.40% when both ends are hinged; the maximum relative error is 9.04% when both ends are fixed; the maximum relative error is 0.55% when one end is fixed and one end is hinged. Therefore, the accuracy of the simplified frame FEM is proved.



(a). Boundary and Loads (Hinged at both ends). **(b).** Boundary and Loads (Fixed at both ends). **(c).** Boundary and Loads (Fixed at one end, free at the other).



(d). First buckling mode (Hinged at both ends). **(e).** First buckling mode (Fixed at both ends). **(f).** First buckling mode (Fixed at one end, free at the other).

Figure 4. Boundary Conditions, Loads and the First buckling mode of simplified beam-column frame FEMs.

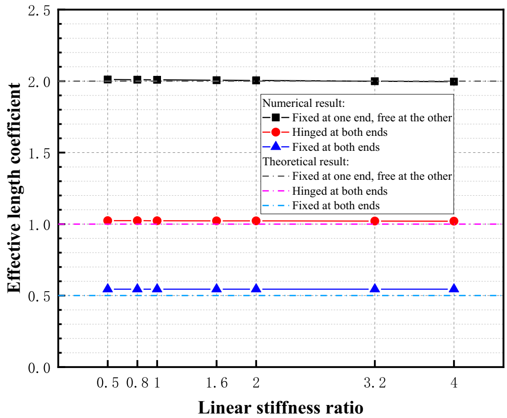


Figure 5. Comparison of Numerical and theoretical effective length coefficients..

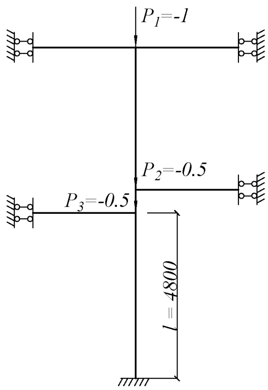


Figure 6. Boundary conditions and loads of irregular steel Non-sway frame columns.

3.4. Parametric Study and Buckling Performance of Irregular Steel Frame Columns with Staggered Beams

In this study, a total of 2744 simplified steel frame models were analyzed by using the verified simplified frame FEMs. The staggered beam was considered to investigate its effect on the buckling performance and effective length coefficient of irregular steel frame columns in indoor substation frames, as shown in figure 6. The parameters for each model are shown in table 1 and table 2.

Based on the numerical results, when the staggered spacing d ranges from -2400 mm to -1500 mm the down staggered beam gives strong lateral support to the ground floor frame column, may causing the second-floor frame column to buckle first in the first buckling mode, which is not the subject of this study and not considered herein.

The eigenvalues corresponding to the first-order buckling modes obtained from the numerical results are taken as the critical buckling loads of the frame columns. The effective length coefficients of the irregular steel frame columns with staggered beams are then calculated by using equation (2). The l in equation (2) is the height of the irregular column, which is taken in this model as l=4800mm. The effective length coefficient is plotted together with the staggered space of frame beam in figure 7 from which, it can be drawn that there is a peak in the effective length coefficient when the staggered space is equal to 0. When the staggered space is less than 0, the effective length coefficient tends to increase approximately linearly with the staggered space of the frame beam. When the staggered space is greater than 0, the effective length coefficient decreases with the increase of the staggered space of the frame beam, but then increases to different degrees, with different inflection points for different linear stiffness ratios.

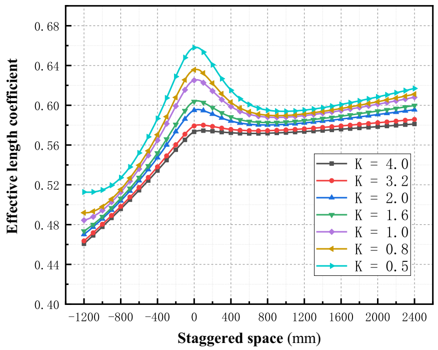


Figure 7. Effective length coefficients of irregular steel non-sway frame columns with staggered beams.

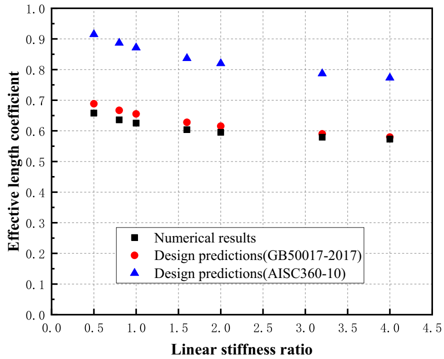


Figure 8. Comparison of effective length coefficient between numerical results and design predictions for regular steel non-sway frame columns.

4. Design Method for Effective Length Coefficients of Steel Non-sway Frame Columns in Indoor Substations

4.1. Regular Steel Frame Columns in Indoor Substations

When the staggered space "d" equals 0, the steel frame columns are regular. The GB50017-2017 [6] and the AISC 360-10 [7] are considered to predict the effective length coefficient of regular steel frame columns. The numerical effective length coefficients of regular frame columns obtained in this study are compared with the predictions by using GB50017-2017 [6] and AISC 360-10 [7], as shown in figure 8. It is shown that the numerical results are relatively consistent with the GB50017-2017 [6] predictions, but there is a gap of about 0.2 with the AISC360-10 [7] predictions.

4.2. Irregular Steel Frame Columns in Indoor Substation

The current design codes do not specify the formula for calculating the effective length coefficients of irregular steel frame columns with staggered beams. Based on the numerical results obtained in this study, the design formulae for calculating the effective length coefficients of irregular non-sway steel frame columns with staggered frame beams in indoor substations are proposed, as shown in equations (4)~ (9).

$$\mu = \begin{cases} C + B_1 d & d \le 0 \\ C + B_2 d + B_3 d + B_4 d & d > 0 \end{cases} \tag{4}$$

$$C = 0.57253 + 0.14863 \times 0.378795^K \tag{5}$$

$$B_1 = 9.40807 \times 10^{-5} + 1.79366 \times 10^{-4} \times 0.27409^K \tag{6}$$

$$B_2 = -9.17504 \times 10^{-6} - 2.55824 \times 10^{-4} \times 0.36893^K \tag{7}$$

$$B_3 = 8.14727 \times 10^{-9} + 1.6704 \times 10^{-7} \times 0.39263^K \quad (8)$$

$$B_4 = -1.49103 \times 10^{-12} - 3.29475 \times 10^{-11} \times 0.39656^K \quad (9)$$

The effective length coefficient of irregular steel frame columns with staggered beams is a binary nonlinear function about the linear stiffness ratio and the staggered space. The numerical effective length coefficients of irregular steel frame columns with staggered beams obtained from this study are used to verify the accuracy of the proposed formulae. The parameter SSE is used in this paper to calculate the sum of squares due to error of proposed design formulae predictions, as shown in equation (10).

$$SSE = \sum_{i=1}^{n} \left(\mu_i - \hat{\mu}_i \right)^2 \quad (10)$$

where μ_i is the numerical effective length coefficient, and $\hat{\mu}_i$ is the predicted effective length coefficient by using the proposed formulae.

The three-dimensional surface representing the proposed design formulae for effective length coefficients of irregular non-sway steel frame columns together with the numerical results are plotted in figure 9. The SSE is equal to 0.0169, depicting that the proposed design formulae gives reliable predictions.

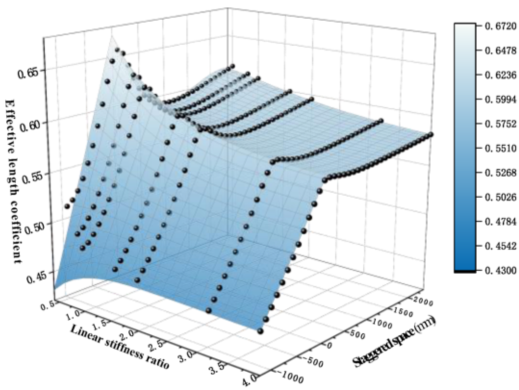


Figure 9. Comparison between FE and proposed effective length coefficients of irregular non-sway steel frame columns with staggered beams.

5. Conclusions

The finite element model for the indoor substation steel frame was developed and verified in this paper. The effect of frame beam staggered space on the effective length coefficients of irregular steel frame columns has been investigated. Based on the numerical results, the effective length coefficient design formulae for irregular steel frame columns with staggered beams are finally proposed. The main conclusions are as follows.

(1) For steel frame columns without lateral displacement, when the staggered space is equal to 0, there is a peak in the effective length coefficient. When the staggered space of the frame beam is lower than 0, the effective length coefficient has a tendency to rise roughly linearly. When the staggered space is greater than 0, the effective length coefficient initially decreases and then increases with the increase of staggered space, and different linear stiffness ratios imply various inflection points.

(2) Based on the numerical results obtained from this study, the design formulae to calculate the effective length coefficients for irregular steel frame columns with staggered beams in frames without and with lateral shifts are proposed. The effective length coefficients of irregular steel frame columns predicted by using the proposed design formulae can accurately reflect the influence of the misalignment height of frame beams.

References

[1] Liang H, Xie Q. System vulnerability analysis simulation model for substation subjected to earthquakes. IEEE Transactions on Power Delivery. 2022; 37(4):2684-2692.
[2] Mohammadi RK, Mosaffa E. Seismic rehabilitation of substation equipment by friction pendulum systems. The 2018 Structures Congress, Incheon, Korea, August. 2018.
[3] Xie Q, Bian X, Xu J. Anti-seismic design method for floor electrical equipment in whole-indoor substation. High Voltage Engineering. 2020; 46(6): 2155-2163.
[4] White DW, Hajjar JF. Buckling models and stability design of steel frames: A unified approach. Journal of Constructional Steel Research. 1997; 42(3):171-207.
[5] Chen J. Stability of steel structure theory and design. Beijing: Science Press, 2014. (in Chinese)
[6] Ministry of Construction of the People's Republic of China. GB50017-2017 Code for design of steel structures. Beijing: China Planning Press, 2017. (in Chinese)
[7] America Institute of Steel Construction. ANSI/AISC 360-10. Specification for structural steel buildings. Chicago, 2010.
[8] ABAQUS, ABAQUS Standard User's Manual 2021, in: Dassault Systemes Simulia Corp, Providence, RI, USA, 2021.