

ELASTIC AND GEOMETRICALLY NONLINEAR BUCKLING RESPONSE OF HEA STEEL COLUMNS WITH VARYING END RESTRAINTS

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ABSTRACT

The buckling behavior of HEA steel columns, which are widely used as columns and frame members in steel structural systems, is directly influenced by parameters such as member length, material properties, and end support conditions. In conventional design, column ends are generally idealized as either pinned or fixed. However, in practice, column end behavior may vary between these two ideal conditions. In this study, the effects of end rotational stiffness on the elastic buckling and geometrically nonlinear buckling behavior of HEA steel columns were investigated numerically. A 5000 mm long HEA200 steel column was modeled in ABAQUS using S4R shell elements. The weak-axis rotational restraint was represented using connector elements. The dimensionless parameter ρ , defined as the ratio of the connector rotational spring stiffness to the column's characteristic flexural stiffness, was investigated over a wide range, from pinned to fixed-end behavior. Eigenvalue buckling loads obtained from the finite element analyses were compared with theoretical Euler solutions for commonly used ideal end conditions. For each model, the first buckling mode was defined as the initial geometric imperfection with an amplitude of $L/1000$, and Static Riks analyses were performed. The nonlinear buckling behavior of the columns was evaluated using the load proportionality factor ($LPF = P/P_{cr}$) and the weak-axis lateral displacement (U_1) at column mid-height. The results showed that increasing end rotational stiffness increased the elastic critical buckling load and reduced the effective length factor. As the normalized load approached the critical region, lateral displacements increased, and the influence of end rotational stiffness became more pronounced. At high ρ values, both the elastic and geometrically nonlinear responses approached the fixed-end condition asymptotically.

Keywords: HEA steel column, rotational stiffness, eigenvalue buckling analysis, initial geometric imperfection, Static Riks analysis.

INTRODUCTION

Buckling is one of the main stability problems governing the load-carrying capacity of slender steel columns under axial compression. In the classical Euler approach, the critical buckling load is defined as a function of member length, flexural stiffness, and end boundary conditions. In real structural systems, however, column-end behavior may fall between the ideal pinned

and fully fixed conditions. Experimental studies have shown that connections assumed to be pinned may still provide a certain level of rotational stiffness, while connections assumed to be fixed may allow some rotation. For this reason, representing actual connection behavior as semi-rigid provides a more realistic description of column stability than the two ideal boundary conditions (Jones et al., 1980).

The effect of end rotational stiffness on column stability has been investigated for many years using analytical and numerical approaches. Kishi et al. (1997) examined the effective length factor of columns in sway frames with semi-rigid connections and showed that the moment–rotation characteristics of the connections should be considered when determining effective length. The study also emphasized the importance of considering second-order effects together with connection stiffness in semi-rigid systems. Raftoyiannis (2005) reported that connection flexibility can significantly reduce the buckling load of steel frames and should be explicitly included in stability analysis. Similarly, Mageirou and Gantes (2006) investigated sway, non-sway, and partially sway multistory frames with semi-rigid connections and represented the rotational restraints at column ends by equivalent springs. An effective length approach was developed and showed good agreement with finite element results. The study also demonstrated that some idealized code-based methods may lead to considerable deviations for semi-rigid systems. Adman and Saidani (2013) represented rotational and translational restraints by springs and examined the relationship between dimensionless end-restraint parameters and the effective length factor. The results showed that boundary conditions in actual structural systems may vary over a wide range between ideal pinned and fixed cases.

More recent studies have also confirmed the major influence of end restraints on critical buckling load. Slimani et al. (2023) developed a parametric approach that considered the boundary conditions of columns and adjacent members in steel frames. The results showed that increasing rotational stiffness reduces the effective length factor and increases the elastic buckling capacity. Koo et al. (2023) modeled different rotational restraints in wide-flange steel columns using rotational springs and reported a significant influence of rotational stiffness on effective length and buckling resistance. ABAQUS S4R shell elements were used, and elastic buckling behavior was evaluated numerically for different levels of rotational stiffness.

The finite element method is a useful tool for stability problems involving complex boundary conditions and complements analytical approaches. Eigenvalue buckling analysis can be used to determine the critical load and associated buckling modes of a structural system. Studies on different steel structural systems have shown that eigenvalue analysis can also be used effectively to verify analytical solutions and proposed buckling formulations. Guzmán and González del Solar (2025), for example, compared the global elastic buckling loads of lattice columns using analytical, numerical, and experimental approaches and reported good accuracy for the proposed critical-load expressions. Wu et al. (2024) also verified elastic buckling formulations using finite element eigenvalue analyses. Although these studies considered different structural systems, the results support the use of analytical solution–eigenvalue finite element comparisons as a reliable verification approach for critical buckling load predictions.

However, eigenvalue buckling analysis is based on an ideal geometry and cannot directly capture deformation development during loading or second-order effects in real columns. Initial geometric imperfections caused by fabrication and erection are unavoidable in steel columns. Raftoyiannis and Ermopoulos (2005) showed that such imperfections have a significant effect on the stability and load-carrying capacity of steel columns under compression and examined these effects using nonlinear finite element analyses. Similarly, Horsangchai et al. (2024) introduced the first buckling mode obtained from linear eigenvalue analysis into the nonlinear model as an initial geometric imperfection and used an imperfection amplitude of $L/1000$ for global buckling.

Defining the initial imperfection from an eigenvalue buckling mode is also widely used in advanced analysis methods. Chan et al. (2025) stated that the shape and amplitude of the initial geometric imperfection play an important role in GNIA and GMNIA results and systematically examined the use of scaled linear buckling modes as initial imperfections. Koo et al. (2023) also introduced the first buckling mode into the nonlinear model as an initial curvature and adopted a maximum imperfection amplitude equal to $1/1000$ of the column length. This approach provides a direct link between the critical state obtained from eigenvalue analysis and the geometrically nonlinear load–displacement response.

A general review of the literature shows that the effects of semi-rigid connections, frame stability, effective length factor, end rotational stiffness, and initial geometric imperfections on column behavior have been studied extensively. However, studies systematically investigating a single wide-flange steel column over a broad range of end rotational stiffness, from pinned to fixed behavior, while using a dimensionless stiffness parameter and evaluating the same models through both elastic eigenvalue buckling and geometrically nonlinear analyses with initial imperfections, are still limited. In this study, the weak-axis buckling behavior of 5000 mm long HEA200 steel columns was investigated numerically under different levels of end rotational stiffness. The finite element model was first verified against Euler solutions for ideal boundary conditions, and the critical buckling loads were then determined by eigenvalue buckling analyses. In the final stage, an initial imperfection with an amplitude of $L/1000$ was defined based on the first buckling mode, and the geometrically nonlinear load–lateral displacement response was examined using Static Riks analyses. The study aimed to determine the effect of end rotational stiffness on both the elastic critical buckling load and the second-order response as the column approaches the critical load.

FINITE ELEMENT MODELING

Column geometry, material properties, and finite element mesh characteristics

The numerical study was carried out on a 5000 mm long HEA200 steel column. The column was modeled in ABAQUS/Standard using a three-dimensional shell representation. The flange and web plates were discretized with four-node reduced-integration S4R shell elements. A

characteristic element size of 10 mm was used for the finite element mesh. Since the study was limited to elastic buckling and geometrically nonlinear stability behavior, steel was treated as a linearly elastic material, and its material and cross-sectional properties were held constant across all parametric models. The elastic modulus was taken as 210 GPa and Poisson's ratio as 0.30. The second moment of area about the weak axis of the idealized HEA200 shell cross-section was taken as $I = 13,337 \times 10^6 \text{ mm}^4$, which is slightly lower than the nominal tabulated value due to the geometric idealization of the rolled section. This approach ensured that changes in the results were caused only by the end rotational restraint. The finite element model of the column is shown in Figure 1.a. Both end sections of the column were connected to reference points using coupling constraints. Translational boundary conditions and the axial load were applied through the reference points. This modeling approach allows the end-section behavior to be controlled from a single point and provides a consistent transfer of the rotational spring action to the column cross-section.

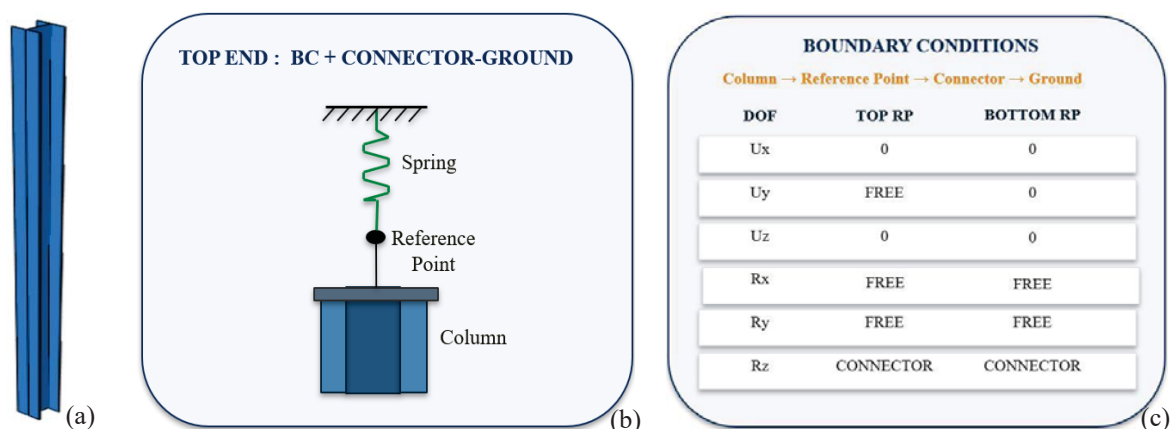


Figure 1. (a) finite element model, (b) support detail at the top end of the column, (c) boundary conditions.

Boundary conditions and connector-to-ground rotational spring

Boundary conditions were first defined at the column model's reference points. The rotational degree of freedom associated with weak-axis bending was controlled through connector elements attached to the reference points. To model the semi-rigid end restraint, the reference point at each column end was connected to the ground by a connector element. Rotational stiffness was assigned only to the rotation associated with weak-axis buckling, and the connector stiffness was defined as $D44 = K_Q$, where K_Q denotes the rotational spring stiffness of the connector-to-ground element. At the upper end, axial translation was left free to allow the applied compressive load, while the transverse translations were restrained. At the lower end, all translational degrees of freedom were restrained. The remaining rotational degrees of freedom were released, while the weak-axis rotation was controlled by the connector-based rotational spring. In this way, the influence of end rotational restraint on the global weak-axis buckling response of the column could be examined independently. The support detail at the upper end is shown in Figure 1.b, while the boundary conditions at the lower and upper ends are presented in Figure 1.c. To compare rotational stiffness independently of column length and

section properties, a dimensionless rotational stiffness parameter, ρ , was used: $\rho = K_Q L / EI$ where K_Q is the connector-to-ground rotational spring stiffness, L is the length of the column, E is the elastic modulus, and I is the second moment of area about the weak axis. The same rotational stiffness value was assigned to both the upper and lower ends of the column in each model. The selected parameter range covers a wide transition from pinned behavior to highly restrained end conditions.

Eigenvalue buckling analysis and Euler verification

Before the parametric study, the finite element model was verified to ensure it accurately reproduced the elastic buckling capacity under ideal end conditions. To verify the model, the eigenvalue critical loads obtained for pinned-pinned, fixed-pinned, and fixed-fixed boundary conditions were compared with the classical Euler buckling solutions. The elastic critical buckling load according to Euler theory is expressed as: $P_{cr} = \pi^2 EI / (KL)^2$ where K is the effective length factor depending on the end boundary conditions. Based on the theoretical effective length factors given in AISC (2022), K values of 1.0, 0.7, and 0.5 were adopted for the pinned-pinned, fixed-pinned, and fixed-fixed conditions, respectively. As shown in Table 1, the differences between the finite element results and the theoretical Euler values remained below 2% for all three ideal cases. This agreement confirms that the shell-based finite element model, boundary conditions, and buckling analysis procedure provide sufficient accuracy for the parametric study.

Table 1. Comparison of finite element eigenvalue critical loads with Euler theory.

Boundary Conditions	FEM P_{cr} (kN)	Euler P_{cr} (kN)	Error (%)
Pinned-Pinned	1099.8	1105.7	0.53
Fixed-Pinned	2236.6	2256.5	0.88
Fixed-Fixed	4336.4	4422.8	1.95

For the parametric analysis, the same dimensionless rotational stiffness value, ρ , was assigned to both the upper and lower ends of each column model. The selected ρ values were defined to represent a wide range of end conditions, from nearly pinned to flexible, semi-rigid, highly restrained, and fixed. For each parametric model, the equivalent effective length factor was back-calculated from the finite element eigenvalue critical load using the rearranged Euler buckling equation: $K = (\pi/L) \sqrt{EI/P_{cr}}$ where P_{cr} is the critical buckling load obtained from the finite element analysis. Table 2 presents the critical buckling loads for each model and corresponding effective length factors.

Table 2. Results of the parametric finite element analyses.

Model	ρ	K (effective length factor)	P _{cr} (kN)
M1	0	1.00	1099.8
M2	0.1	0.98	1143.8
M3	0.5	0.92	1311.2
M4	1	0.86	1502.1
M5	2	0.78	1831.2
M6	5	0.66	2516.4
M7	10	0.60	3120.6
M8	25	0.54	3751.1
M9	50	0.52	4031.9
M10	75	0.52	4134.5
M11	100	0.51	4187
M12	250	0.51	4285.9
M13	500	0.51	4319.5
M14	1000	0.50	4336.4

GNIA / Static Riks analysis procedure

In the geometrically nonlinear analyses, the first global buckling mode obtained from the eigenvalue buckling analysis was used as the initial geometric imperfection shape for each model. In this way, the initial imperfection was introduced in a form consistent with the column's dominant global buckling response. The imperfection amplitude was taken as $L/1000$, consistent with values adopted in previous studies (Horsangchai et al., 2024; Koo et al., 2023; AISC, 2022). For the columns examined in this study, the maximum initial geometric imperfection was therefore taken as 5 mm. Since the imperfection was defined using the first buckling mode of each model, the effect of end rotational stiffness on the mode shape was also directly reflected in the nonlinear model. For the M1, M6, and M14 models, representing low, intermediate, and high rotational stiffness, respectively, the first mode retained the general character of global weak-axis buckling. As the end rotational restraint increased, however, the curvature distribution along the column changed, end rotations decreased, and the buckling shape gradually approached the fixed-end condition. For this reason, a single common imperfection shape was not used for all models; instead, the first eigenmode of each model was adopted.

The geometrically nonlinear response of the imperfect models was analyzed using the Static Riks method. Figure 2 shows the first buckling modes transferred to the Riks analyses for the pinned (M1), semi-rigid (M6), and practically fixed (M14) models. The Riks method allows the load-displacement equilibrium path to be traced in buckling and post-buckling problems, where conventional load-controlled static procedures may struggle to track the response. For each model, the reference axial load was defined as the elastic critical buckling load, P_{cr} , obtained from the eigenvalue buckling analysis of the same model. Accordingly, the Load Proportionality Factor (*LPF*) calculated during the Riks analysis directly represented the normalized axial load level: $LPF = P/P_{cr}$ where P is the current axial load acting on the

column during the analysis and P_{cr} is the eigenvalue critical buckling load of the corresponding model. This definition allowed models with different end rotational stiffness values and different absolute critical loads to be compared at the same normalized load levels. In particular, comparing the weak-axis lateral displacements at column mid-height at normalized load levels of $LPF = 0.75, 0.90$, and approximately 0.95 allowed the effect of end rotational stiffness on the development of geometrically nonlinear deformation to be evaluated more clearly.

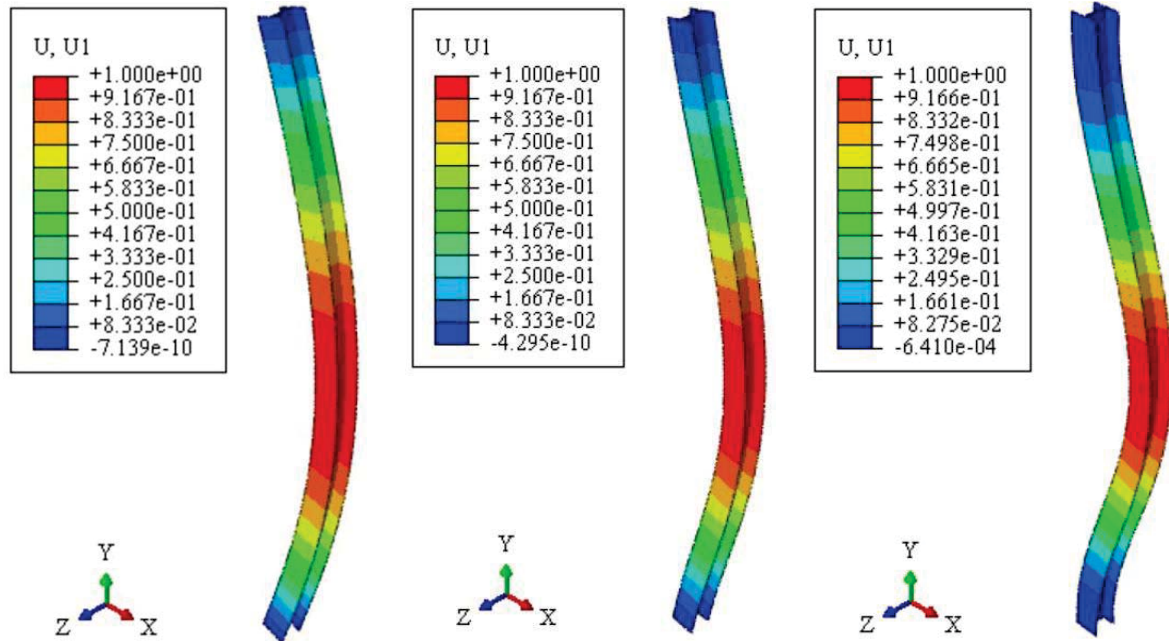


Figure 2. First buckling modes of models M1, M6, and M14, respectively.

RESULTS AND DISCUSSION

Table 2 emphasizes the impact of the end rotational stiffness on the elastic critical buckling capacity of the column. Without changing the cross-section, member length, or material properties, increasing only the end rotational stiffness can increase the elastic stability capacity by nearly fourfold. In the $P_{cr} - \rho$ curve shown in Figure 3, the most rapid increase in capacity occurs within the low and intermediate stiffness ranges. At high ρ values, the rate of increase becomes much smaller. This saturation trend is related to the fact that end rotations are already largely restrained at high stiffness levels. Therefore, increasing the connector stiffness beyond a certain level provides only a limited increase in the elastic critical load.

As shown in Figure 3, the finite element solution approaches the theoretical fixed-fixed limit at high rotational stiffness levels. This confirms that the parametric model provides a physically consistent transition between the ideal end conditions. Compared with examining only the pinned and fixed cases separately, this transition also shows the stiffness range in which rotational restraint has the greatest effect on the critical load. As the rotational spring stiffness increases, rotational freedom at the column ends decreases, the global buckling mode develops a shorter effective length, and the critical load increases. The tendency of the effective length factor, K , to level off near 0.5 at high ρ values demonstrates the saturation observed in the $P_{cr} - \rho$ curve.

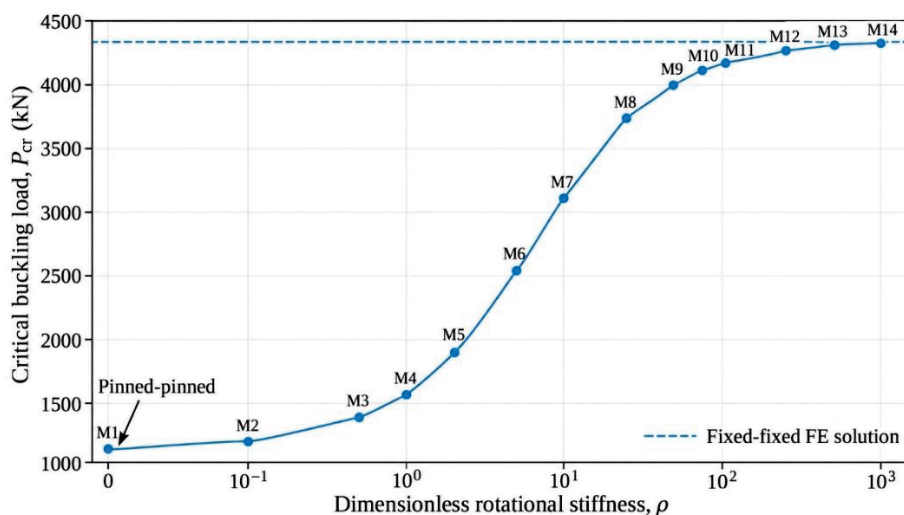


Figure 3. Relationship between the dimensionless end rotational stiffness, (ρ), and the elastic buckling load, P_{cr} .

The Static Riks analyses show how the initial eigenmode-shaped geometric imperfection is amplified along the nonlinear equilibrium path as the axial load increases. The deformed shapes of models M1, M6, and M14 at the $P/P_{cr} \approx 0.95$ level, shown in Figure 4, indicate that global weak-axis flexural buckling remains the dominant mode across all stiffness levels, while the amplitude of lateral displacement varies with the end rotational stiffness. Since the initial geometric imperfection was defined in accordance with the first eigenvalue buckling mode, the same global buckling pattern remained dominant as the load increased, and the second-order displacements became more pronounced as the response approached the critical region.

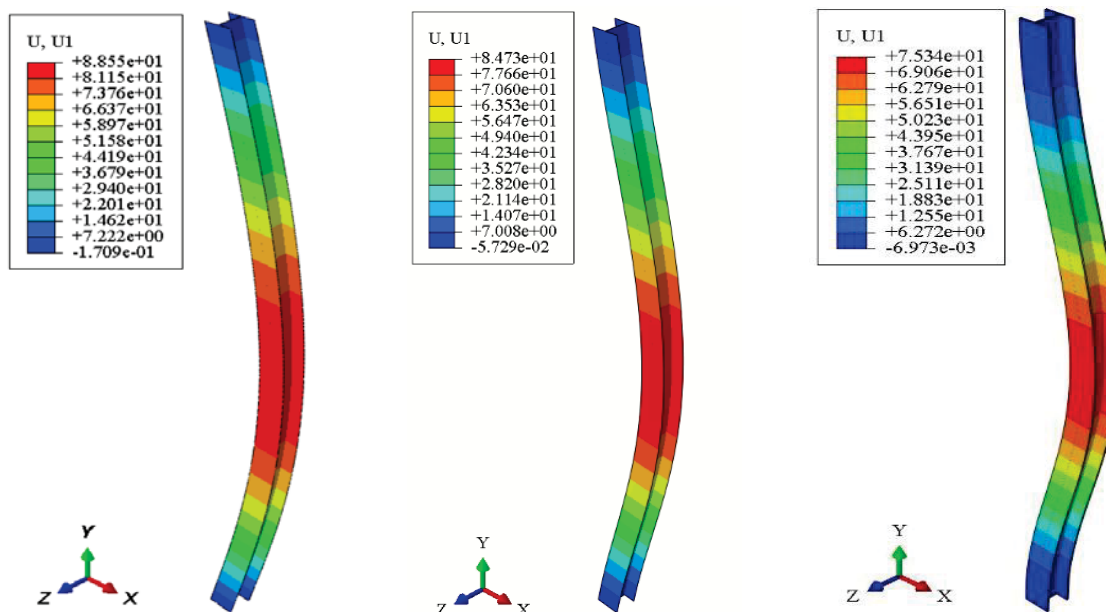


Figure 4. GNIA/Riks deformed shapes of models M1, M6, and M14 at $P/P_{cr} \approx 0.95$, respectively.

The $LPF - U_1$ curves presented in Figure 5 show that lateral displacements remain relatively small at the early stages of normalized loading, while a clear increase in displacement develops as the response approaches the critical region. Since the $LPF = P/P_{cr}$ ratio on the vertical axis is normalized with respect to the elastic critical load of each model, direct comparisons can be

made for different ρ values. At low and intermediate normalized load levels, the curves of the different models largely overlap, indicating that the influence of end rotational stiffness on the normalized lateral displacement remains limited in this range. The increasing sensitivity of the curves beyond $LPF \approx 0.90$ indicates that the effects of the initial geometric imperfection and $P - \delta$ response become more pronounced together. As the response approaches $LPF \approx 0.95$, the curves begin to separate more clearly, with lower end rotational stiffness generally associated with larger lateral displacements. For clarity, representative models spanning the investigated range of end rotational stiffness were selected for comparison in Figure 5.

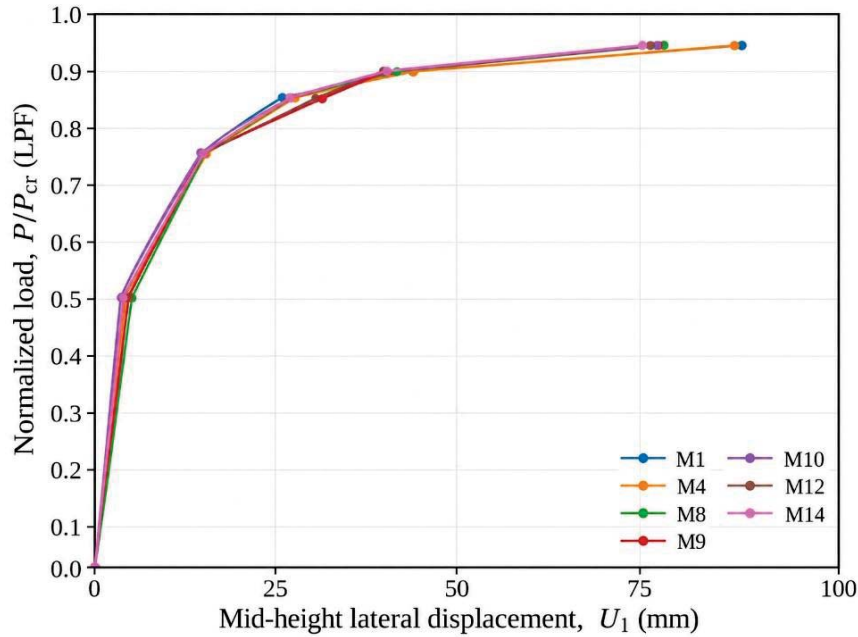


Figure 5. Normalized load–mid-height lateral displacement curves from GNIA/Riks analyses up to the critical response range.

Another notable point in Figure 5 is that different end rotational stiffness values can produce different lateral deformation demands even at the same normalized load level. Columns with stiffer end restraints reach higher axial loads in absolute terms, while the normalized curves show the approach to the critical region consistently. Therefore, the $LPF - U_1$ representation can be used to evaluate the development of lateral deformation at common normalized load levels and to highlight the increasing effect of end restraint as the critical region is approached. In Figure 6, the effect of end rotational stiffness on lateral displacement was quantitatively evaluated by considering the U_1 values at $LPF = 0.75, 0.90$, and approximately 0.95 as a function of the dimensionless rotational stiffness, ρ . At $LPF = 0.75$, the differences between the models are small, with U_1 values ranging from 14.2 to 15.2 mm. At $LPF = 0.90$ level, the lateral displacements increase to approximately 39.6 to 43.4 mm, while the influence of rotational stiffness remains relatively limited. In contrast, at $LPF \approx 0.95$, U_1 ranges from approximately 75.3 to 88 mm. The total spread in U_1 among the models increases from approximately 1 mm at $LPF = 0.75$ to 12.7 mm at $LPF \approx 0.95$, quantitatively demonstrating the increasing influence of end rotational restraint as the critical region is approached. At lower

normalized load levels, geometric nonlinear effects remain relatively limited, whereas near the critical region, amplification of the initial imperfection and second-order effects becomes more significant.

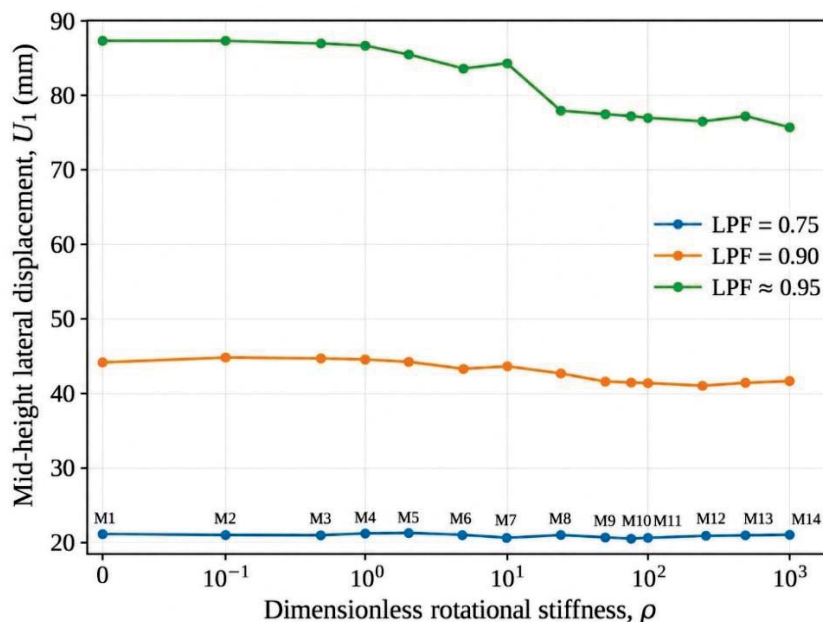


Figure 6. Variation of mid-height U_1 displacement with ρ at selected normalized load levels.

Figure 7 presents the relationship between the maximum attained nonlinear load, $P_{max} = LPF_{max} \times P_{cr}$, and the dimensionless rotational stiffness, ρ . The maximum axial load reached in the Static Riks analyses increases markedly as the end rotational stiffness increases. At low ρ values, the column response approaches the pinned condition, and the maximum load remains relatively low. As the end rotational stiffness increases, rotational freedom at the column ends decreases, and the effective buckling length becomes shorter. As a result, higher axial load levels are reached in the nonlinear analyses. The increase is more pronounced within the intermediate stiffness range, while the curve starts to level off at high ρ values, indicating that the finite element response approaches the fixed–fixed condition. The maximum loads obtained for models M12–M14, approximately 4100 – 4200 kN, are close to the eigenvalue critical buckling load obtained for the fixed-fixed boundary condition. For some models, the reported value corresponds to the highest load reached within the analysis range rather than to a distinct limit point on the Riks equilibrium path. These values should therefore be interpreted as the maximum attained loads within the analyzed response range. The results show that increasing end rotational stiffness significantly improves the geometrically nonlinear load-carrying capacity of the imperfect column. However, the rate of increase gradually decreases at high stiffness levels as the response approaches the fixed-end limit.

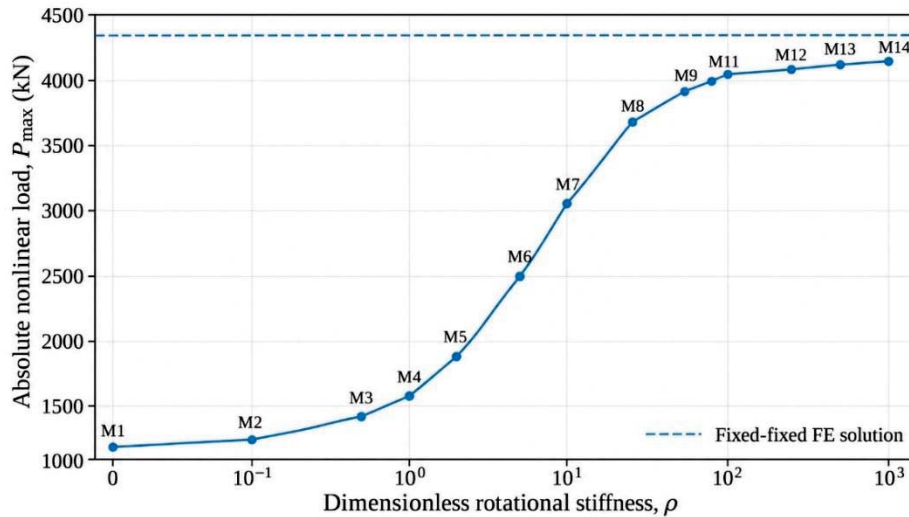


Figure 7. Variation of the maximum attained nonlinear load, P_{max} , with the dimensionless rotational stiffness parameter, ρ .

CONCLUSION

In this study, the elastic and geometrically nonlinear buckling behavior of 5000 mm-long HEA200 steel columns under various levels of end rotational restraint was investigated using eigenvalue buckling and Static Riks analyses. The main findings are summarized below.

- The finite element model developed using S4R shell elements showed good agreement with the Euler buckling solutions under ideal boundary conditions. The maximum relative error was 1.95%.
- As the dimensionless end rotational stiffness increased, the critical buckling load increased, while the effective length factor decreased, indicating a continuous transition from pinned-like to fixed-end behavior.
- The $P_{cr} - \rho$ and $K - \rho$ relationships exhibited a clearly nonlinear trend. The influence of end rotational stiffness was most pronounced at low and intermediate stiffness levels, while the increase in the elastic critical load gradually diminished at high ρ values as the response approached the fixed-end limit.
- In the Riks analyses, including an $L/1000$ initial geometric imperfection, lateral displacements increased more rapidly after the normalized load reached approximately $P/P_{cr} = 0.90$. This behavior indicates the increasing importance of second-order effects as the critical load region is approached.
- At the same normalized load level, columns with lower end rotational stiffness generally developed larger mid-height lateral displacements, and this difference became more pronounced as P/P_{cr} approached 0.95.

End rotational stiffness significantly influences both the elastic critical load and the geometrically nonlinear stability capacity of steel columns. Including initial geometric imperfections and geometric nonlinearity provides a more realistic representation of deformation development and second-order effects than eigenvalue analysis alone. Future

studies may include material nonlinearity, residual stresses, different imperfection amplitudes, and nonlinear moment–rotation relationships.

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