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Research Paper

Analysis of the inelastic lateral - torsional buckling resistances of steel truss members with global and local imperfections

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ABSTRACT

The local and global imperfections of I-shaped steel beams are known to significantly impact the load-carrying capacity of the structure. This is particularly critical for structures subjected to heavy loads, where these factors must be meticulously controlled to prevent potential failures. Therefore, the objective of this project is to describe a numerical analysis that was conducted to evaluate the influence that initial global and local flaws have on the inelastic buckling resistances of steel truss members that are used in steel bridges. These numerical studies are based on Abaqus, and they have been validated quite well against the data that are now available. After that, the numerical models are utilized in order to assess the inelastic buckling resistances of the system, taking into consideration four distinct sorts of initial global and local imperfections which are feasible. The numerical results are compared to the standard evaluations, which are also examined and evaluated. In addition, parametric investigations of the impact of the thicknesses of the web and flange on the inelastic buckling resistances are carried out as part of the current research. The strengthening techniques assessed in this research can serve as a foundation for engineers to implement in actual steel beam structures.

1 Introduction

Due to their various benefits, steel truss constructions are used in many fields worldwide including in Vietnam. Steel constructions are used in houses, industries, bridges, mineral drilling rigs, and other architectural and cultural works [1-4] (Figure 1). They are prefabricated, fast and compact, have a great span/clearance capacity, and are cheaper than other constructions. Steel constructions used for a long time may develop issues that influence their performance. Remaining tension from welding/steel rolling, local or overall warping, corrosion that punctures and lowers the load-bearing cross-section, and partial edge connection cracking are the issues. The above factors may diminish the structure's load-bearing capacity.

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Damaged steel components can be repaired or replaced if conditions allow. Many constructions have defective components that must work for operation and exploitation. Some design standards and most current studies have not yet found a general solution for the resistance of structural components impacted by geometric faults due to their nonlinear properties and difficulty in assessing and evaluating. Local warping deformations, overall warping, and boundary condition flaws also have a major effect on the beam's nonlinear buckling moment [4-10]. According to a search of extant documents, the effect of initial warping fault types on steel truss members' nonlinear moment stability resistance is unclear.

Thin-walled steel members fail in complex ways depending on span length, web and flange strength. For steel beams that have parts of class 1 or class 2 (or solid sections), respectively and not cross-braced, the failure mode can be based on completely plastic cross-section in short unbraced lengths, nonlinear stability resistance in medium lengths, or elastic stability resistance in large lengths [2, 5, 11, 12]. The structure's residual stresses and geometrical imperfections (local buckling, structural axis bending) make nonlinear stability resistance a complicated failure mode [5, 12-15]. Local and global stability phenomena also depend on steel modulus of elasticity, Poisson's coefficient, width-thickness ratio, and slenderness factor. CSA S16 [11] and Eurocodes 3 [5] limit unbraced beam length initial curvature to $L/1000$.



(a) Local imperfection in steel columns [1]



(b) Local imperfection at the truss of the Chuong Duong bridge

Fig. 1 – Some typical problems and damages in steel beam

Based on that basis, the paper will conduct a study for the purpose of assessing the impact inelastic buckling on the resistance of steel truss bars. The paper will present methods for evaluating and calculating the nonlinear stability resistance of steel truss bars. Analytical and numerical models are developed in the Abaqus software, integrating the remaining strains and first flaws to determine the nonlinear moment resistance of the steel truss to be constructed. From there, the paper will present solutions to increase the magnitude of the flange and web thickness or use additional reinforcing ribs to strengthen the steel truss structure and finally draw conclusions and recommendations for research directions.

2 Evaluation of the impact of the initial imperfections on the inelastic buckling resistances of steel truss members

Much research has examined steel structure nonlinear moment resistance with the remaining strains and first mode shape [15-24]. The interplay between initial imperfections and residual stresses in these papers remain unexamined. Because there are no analytical theoretical models or general numerical solutions to properly evaluate the effect of buckling deformation on steel beam structures' nonlinear stability resistance, this study will develop them.

2.1 Evaluation method

The paper uses Abaqus software to analyze the longitudinal resistance in steel truss structures considering material nonlinearity and geometric nonlinearity. The structural problem of the paper is constructed as Figure 2 and Figure 3, a simple beam with load P in the middle of the span with span length $L = 4\text{m}$ and cross-section of $W250 \times 45$. Within the limits of the paper, we only consider the case of compressive load and the effect at the center of the section. Basic cross-sectional dimensions of truss bars are respectively with the following parameters: $b = 148\text{mm}$; $t_f = 13\text{mm}$; $h_w = 240\text{mm}$; $t_w = 7.6\text{mm}$; $F_y = 350\text{N/mm}^2$; $A = 5474.4\text{mm}^2$; $I_y = 7032662\text{mm}^4$; $N_p = 1858.559\text{kN}$; $L = 4000\text{mm}$ $E = 200000\text{N/mm}^2$; $N_{cr} = 866.7405\text{kN}$.

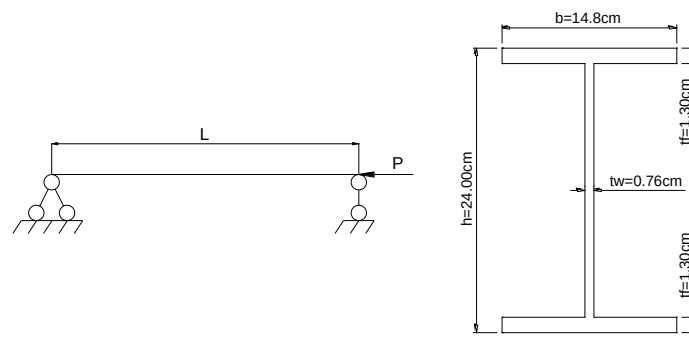


Fig. 2 – Describe the problem with an indication of where the load P is situated at the cross section

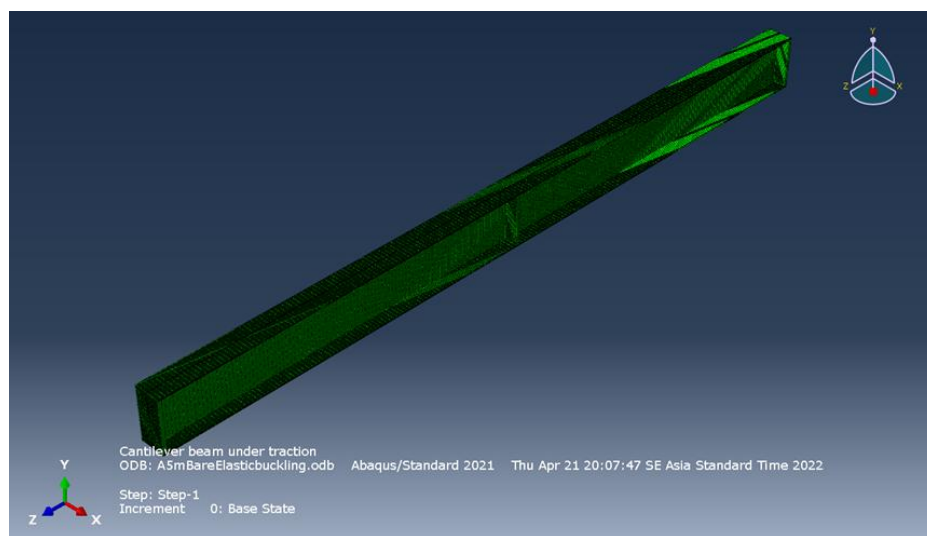


Fig. 3 – 3D Modeling of Steel beams

2.2 Numerical model integrating initial imperfections in Abaqus software

Nonlinear analysis of steel structures is often quite complicated. Most of the studies focus on a certain type of structure [2-5]. Therefore, the present study chooses a simple wide-flanged steel truss to analyze the impact of initial imperfections on the nonlinear stability resistance of the steel truss. Specifically, a simple steel truss subjected to an axial force P (Figure 2) is considered. The truss has a span length L and it has a constant cross-section W250x45. Steel is regarded as a completely pliable material with a modulus of elasticity. $E=200\text{GPa}$, a yield strength $F_y=350\text{Mpa}$ and a coefficient $\nu=0.3$. When calculating the nonlinear stability resistance of the truss, it is necessary to take into account the potential impacts of residual stress as well as initial imperfections.

To build the code for the structure of the article, firstly, we still create *Heading. Then create element nodes according to the *Node command. Then create elements according to the *Element command. Material properties are defined via the *Solid section command. The Abaqus models built in this work use the library's C3D8R three-dimensional solid elements to appropriately characterize the model's behavior in elastic and nonlinear stability analysis problems. The three-dimensional element has 8 nodes with 3-line displacements in 3 directions. This element has 24 degrees of freedom and a central integration point.

Setting up boundary conditions: The boundary conditions of the simple truss are shown in Figure 4, at the two ends of the truss, the boundary condition creation commands applied are: *Boundary (Node1C0), 2 (Node1C0), 3 (Node1CL), 2 U2latalfixat0, 1 U2latalfixatL, 1.

Initial Imperfections integration: In the present study, four types of initial deformations are considered, including 3 global warping deformations and 1 local warping deformation (Fig. 5). For global imperfections of the member axis, an allowable

initial deformation of the bar axis is $L/1000$ where L represents the unbraced length. For local deformations, in addition, it is presumed that the flange and web of the steel beam adhere to the acceptable limits that were discussed earlier. The local warping amplitude is assumed to be 4mm.

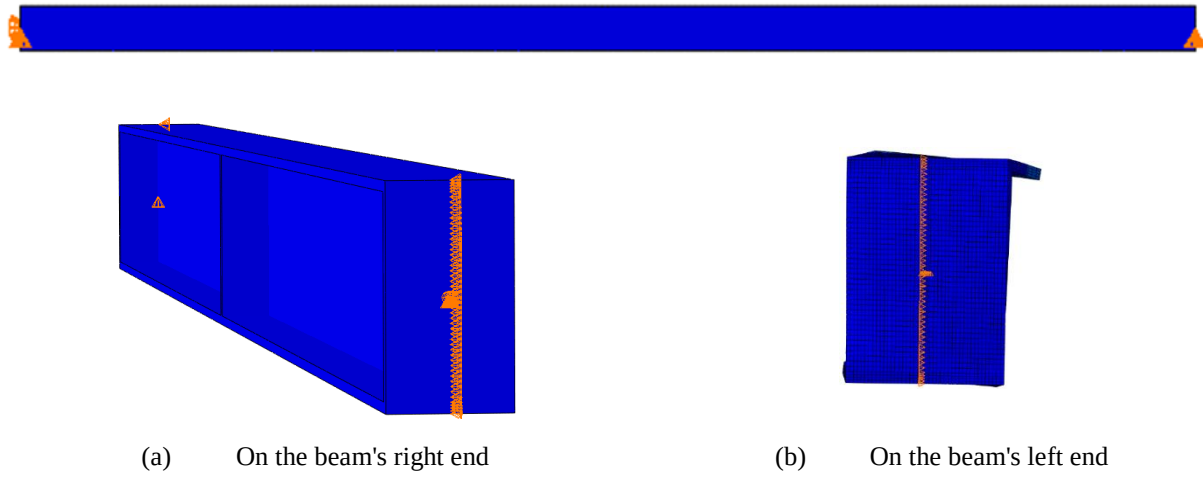


Fig. 4 – Boundary conditions of structures in Abaqus model

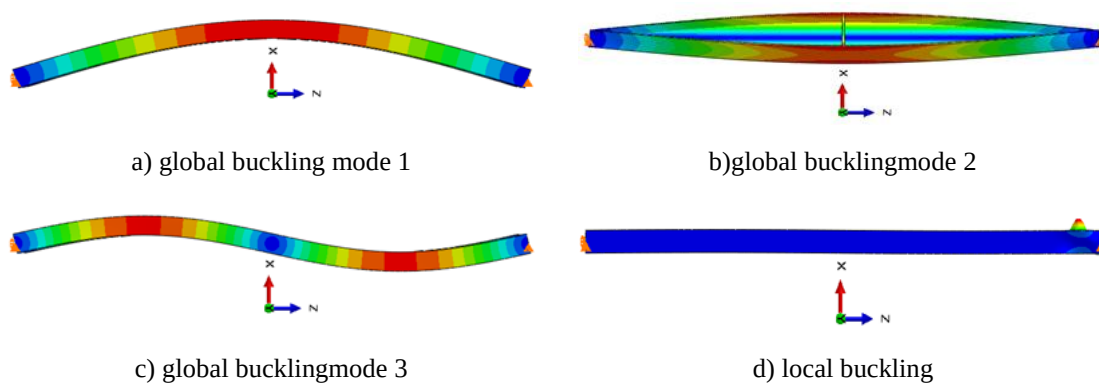


Fig. 5 – The type of buckling

2.3 Numerical standard evaluation for the inelastic buckling resistances

2.3.1 Calculate resistance according to TCVN 5575-2021 standard [2]

Strength calculations for tensile members at centre point (Taken according to Formula 1, Section 7.1.1) [6]

$$\sigma = \frac{N}{A_n} \leq f \gamma_c \quad (1)$$

From formula(1), the centric compressive force is

$$N_b = f \cdot \gamma_c \cdot A_n \quad (2)$$

where:

- A_n : the actual cross-sectional area of the member within the structure.

- γ_c : the coefficient condition of the structure, $\gamma_c = 0.9$ Table 3 Section 5.4.2 TCVN 5575-2012
- f : the calculated strength of the compressive steel taken according to the yield limit $f = f_y / \gamma_m$.

Calculation of buckling resistance:

Calculation of buckling of solid structure subjected to true compression according to formula (Formula 20, section 7.3.2.1 in standard)

$$\frac{N}{\varphi A} \leq f \gamma_c \quad (3)$$

From formula(3), the compression of centre compression member is

$$N_{0d} = f \cdot \gamma_c \cdot \varphi \cdot A \quad \delta = \sum_{i=1}^s e^H(\omega_i) e(\omega_i) \quad (4)$$

2.3.2 Calculate resistance according to Eurocode 3: Design of steel structures – Part 1-1: General rules and rules for buildings [5]

Compression:

The design value of the compression force N_{Ed} at each cross section shall satisfy (Taken according to Formula 6.9, Section 6.2.4)

$$\frac{N_{Ed}}{N_{c,Rd}} \leq 1,0 \quad (5)$$

where:

- In order to effectively determine the cross-sectional design resistance under uniform compression $N_{c,Rd}$, the following should be done

$$N_{c,Rd} = \frac{A f_y}{\gamma_{M0}} \quad (6)$$

Consistent components under compression:

Following these steps will ensure that a compression member does not buckle

$$\frac{N_{Ed}}{N_{b,Rd}} \leq 1,0 \quad (7)$$

where:

- The design buckling resistance of the compression member $N_{b,Rd}$ ought to be ascertained by way of

$$N_{b,Rd} = \frac{\chi A f_y}{\gamma_{M1}} \quad (8)$$

The relevant buckling mode's reduction factor, denoted as χ , is determined in section 6.3.1.2 of Eurocode 3.

2.3.3 Calculate resistance according to CSA [11]

For structures that are twice symmetrical, the factored axial compressive resistance C_r is defined as

$$C_r = \frac{\phi A F_y}{(1 + \lambda^{2n})^{\frac{1}{n}}} \quad (9)$$

where:

- $n = 1.34$ for hot-rolled structural sections, fabricated structural sections, and hollow structural sections that were constructed in accordance with CSA G40.20, Class C (cold-formed non-stress-relieved), ASTM A500, or ASTM A1085
- $\lambda = \sqrt{\frac{F_y}{F_e}}$ with $F_e = \frac{\pi^2 E}{\left(\frac{KL}{r}\right)^2}$

2.4 Validate the results and compare the results with the values specified in the design standards

Figure 6 shows that the force-displacement curve of this investigation peaks at 1900.4 kN and 32.2 mm axial displacement. After this apex, force drops and displacement increases. The numerical solution of this investigation yields 1900.4 kN plastic resistance. According to popular standards (Vietnam, Canada, Europe), the beam's plastic resistance is 1925.7 kN. The difference between these options is 1.3%. Thus, the present study's solution matches the typical plastic resistance solution.

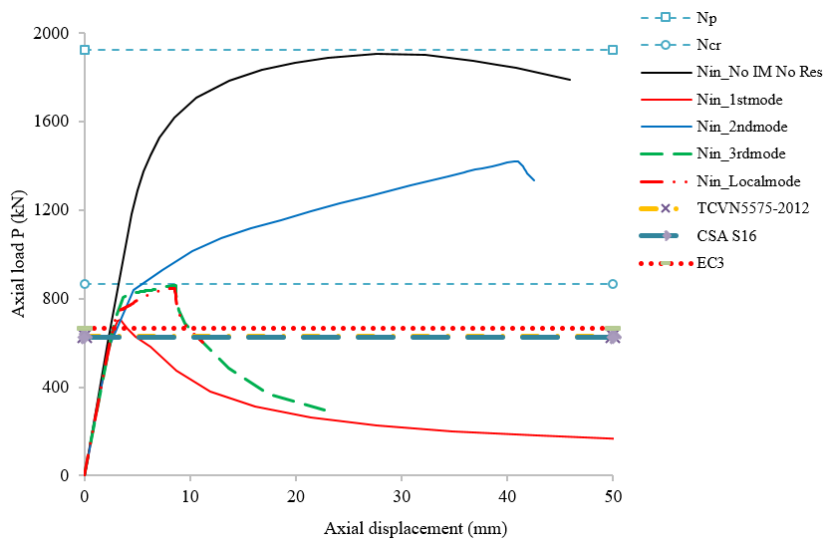


Fig. 6 – The comparison of the results of calculation of nonlinear axial force of structures with different types of buckling, obtained based on numerical solutions, with the results of calculations according to some common standards

These inferences can be derived from Figure 6: The results of solutions based on different criteria vary greatly. The TCVN5575-2012 standard gives a nonlinear stable axial compressive strength of 629.92 kN. The CSA S16 value is 625.42, 0.71% lower than the reference value. The EC 3 standard value is 665.92 kN, 5.64% greater than the reference value. The numerical research solution is consistent and closest to EC 3 and differs from TCVN and CSA S16. The numerical solution is prudent and safer (lower) than TCVN and CSA S16.

3 Effects of the web thickness, flange thickness and web stiffeners on the inelastic buckling responses of the steel truss members

Adding web thickness, flange thickness, or reinforcing stiffeners (Figure 7) might improve the structure's bearing capacity when deformed. The reference structure is a basic truss bar with span $L=4.0\text{m}$, and cross-section $W250\times45$ carrying central compressive load (Figure 2) to test these solutions. One parameter change, while the structure's other parameters remain the same as the reference truss bar. Figures 5 show the beam's early bending. Section 2's Abaqus simulation approach calculates the structure's force-axial displacement curves. Below are the trusses bar reinforcing solution efficacy evaluation results.

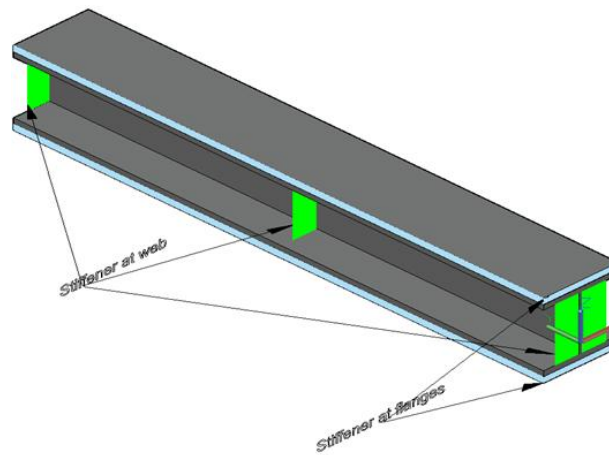


Fig. 7 – Reinforcing the steel beam by adding extra thickness to the web, flange and adding mid-span stiffeners to the web

3.1 Detailed evaluation of the effect of the solution to increase the thickness of the steel web and flanges

Figure 8 shows the relationship between the axial force P and the maximum deflection of the truss bar strengthened by increasing the flange t_f thickness from 13mm (reference beam) to 17mm. The nonlinear buckling load of the truss bar with the reference flange thickness ($t_f = 13\text{mm}$) is 703.1kN. From 13mm to 15mm reinforced flange thickness, this peak is 810.5kN. Thus, increasing flange thickness increases axial resistance by 15.3%. Increasing the reinforced flange thickness from 13mm to 17mm increases this peak to 911.6kN, increasing axial resistance by 29.7%. Thus, increasing flange thickness considerably increases truss bar nonlinear buckling resistance.

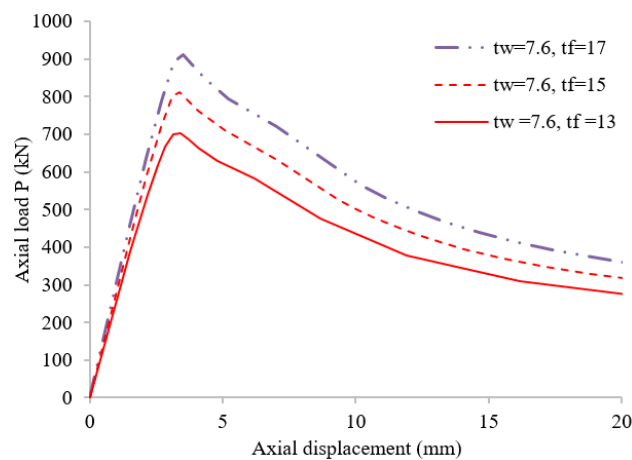


Fig. 8 – Reinforcing steel beams by increasing the thickness of the flange

Figure 9 demonstrates the connection between axial load P and maximum deflection of the truss bar reinforced by increasing web thickness from 7.6mm (reference beam) to 12mm. Nonlinear buckling load is 703.1kN for truss bar with reference web thickness ($t_w = 7.6\text{mm}$). This peak is 712.8kN when the web is reinforced from 7.6mm to 10mm. Increasing flange thickness increases axial resistance by 1.38%. This peak is 726.1kN when the flange is reinforced from 7.6mm to 12mm, increasing axial resistance by 3.27%. Accordingly, increasing web thickness marginally (insignificantly) increases structural nonlinear buckling resistance.

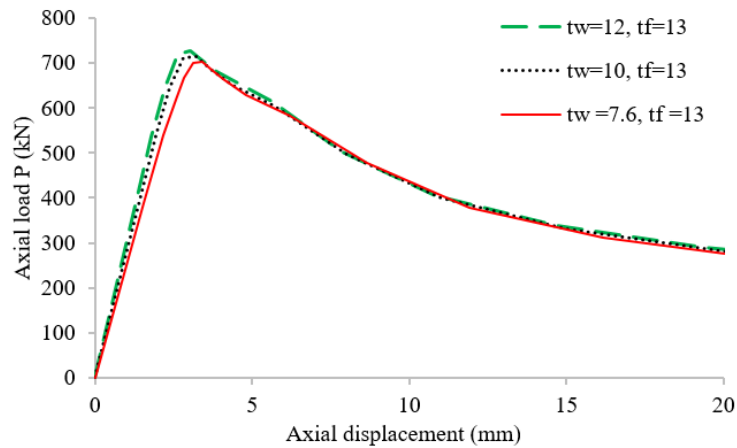


Fig. 9 – Reinforcing steel beams by increasing the thickness of the web

3.2 Detailed evaluation of the effect of the stiffeners at the web

Three 8mm steel stiffeners reinforce the web: one in the middle of the span and two at each beam end. Abaqus runs the analytical model. The reinforced beam structure fails due to global buckling type 1, 2, 3, and local buckling.

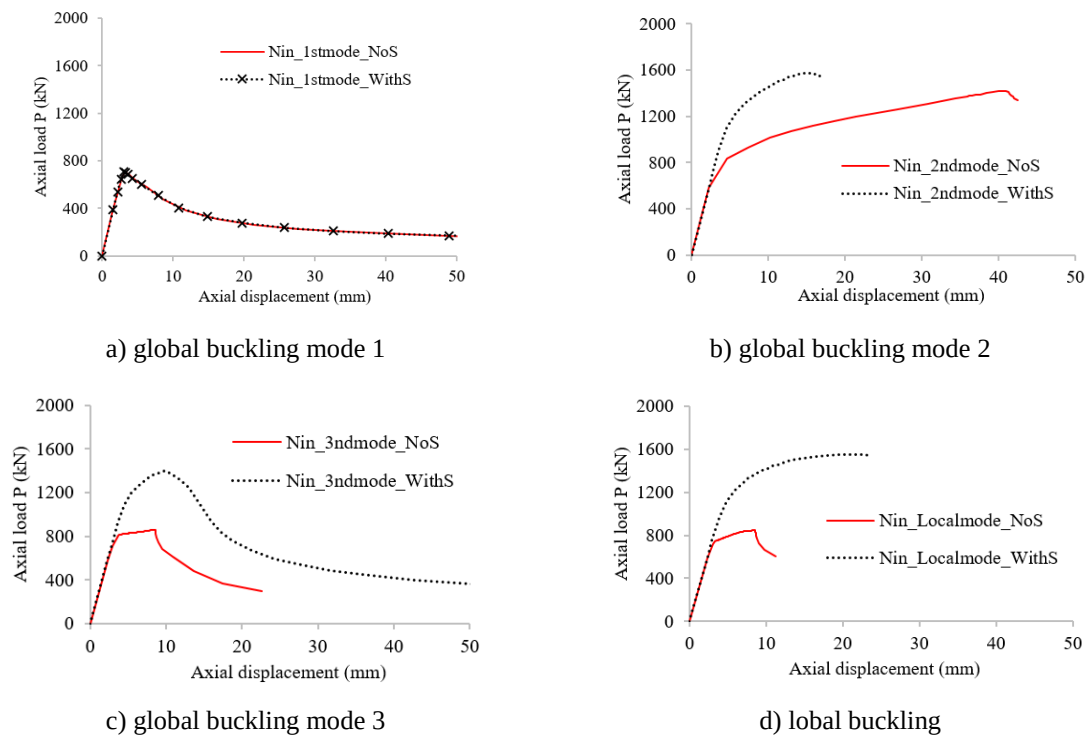


Fig. 10 – Axial load and axial displacement relationships of beams without and with web reinforcement by vertical stiffeners for 3 global bucklings and 1 local buckling type

In Figure 10a, without the stiffeners, the peak of the nonlinear buckling load of the truss is 703.1 kN. With the stiffeners, this peak is 705.2 kN. The solution of using the reinforcing ribs helps to increase the moment resistance by only 0.3%. Thus, the stiffeners have almost no stiffeners effect on the structure affected by warping type 1. With Figure 10b, without the stiffeners, the peak of the nonlinear buckling load of the beam is 1420.7 kN. With the stiffeners, this peak is 1570.5 kN. The solution of using the stiffeners helps to increase the moment resistance by 10.6%. Thus, the stiffeners have a significant effect on strengthening the bearing capacity of the structure affected by warping type 2. With the results in Figure 10c, without the stiffeners, the peak axial force P is 860.9 kN. With the stiffeners, this peak is 1397.3 kN. Adding stiffeners to a structure is a great way to boost its bearing capacity by as much as 62.3 percent. Consequently, the structure impacted by type 3 warping has its bearing capacity significantly enhanced by the stiffeners. Finally, in Figure 10d, without the stiffeners, the peak axial force P is 847 kN. With the stiffeners, this peak is 1553.9 kN. The solution of using stiffeners helps to increase the moment resistance by 83.5%. Thus, the stiffeners have a significant effect on strengthening the bearing capacity of the structure affected by warping type 4. For the case of local instability of the web of the steel beam, the use of the stiffeners increased the moment resistance to 83.5%, a very significant number for the 3 cases of overall instability above. Local instability of steel beams can occur when the thickness of the steel plates is thin but the height of the column cross-section or the width of the column flange is large. However, as presented in section 3.1, increasing the thickness of the web plate only contributes slightly (insignificantly) to the nonlinear stability resistance of the structure. As for the method of adding the stiffeners to the web plate, it increases the moment resistance to local instability by up to 83.5%.

4 Conclusions

With comparisons based on numerical models and standard-based formulae, the paper provides a detailed evaluation of the impact of local and global imperfections, thereby proposing effective solutions for mitigation. Without initial local imperfections, the structure's compressive force-displacement curve is near to the beam's design plastic resistance. Buckling distortion considerably reduces beam resistance. Global buckling affects truss member nonlinear buckling load differently. Given that there is one kind of local buckling and three kinds of global buckling, the structure's compressive resistance (nonlinear stability) drops from 55.1 to 63.3% compared to its plastic resistance. The buckling deformation amplitude has a substantial effect on steel truss axial resistance for each warping type. A structure with mode type 1 with initial buckling amplitudes of 2.0, 4.0, 6.0mm, 8.0, and 10.0mm has lowered resistances of 60.1, 63.3, 65.3, 67.0, and 68.7% compared to its plastic compressive strength. Nonlinear buckling load solutions by different standards yield different findings. The paper estimated and compared nonlinear buckling load findings for Vietnamese TCVN5575-2012, Canadian CSA S16 is 625.42, and European EC3. Comparing the numerical solutions in the paper demonstrates that the current numerical study solution is consistent and closest to the EC3 standard, but it differs from the TCVN and CSA S16 standards. The current numerical solution is prudent and safer (lower) than TCVN and CSA S16. The report found that the numerical solution's nonlinear stability resistance is higher than the standards when the beam's warping amplitude is less than $L/1000$. The nonlinear stability resistance will be lower than the normal limits when this warping amplitude surpasses the limit. Hence, standard values exceed beam carrying capacity. The investigation on strengthening bearing capacity found that increasing flange thickness greatly boosts truss nonlinear stability resistance. The structure's nonlinear stability resistance grows marginally as the web thickness increases. The paper reveals that reinforcing stiffeners are virtually useless for type 1 warped structures (the truss is warped and loses horizontal stability in one direction; the truss axis is bent). However, they significantly affect buildings with other types of buckling, such as twisted in the center, initially bent in two directions or local buckling truss bars. This technology can be implemented to enhance the resistance of steel beam structures in practice.

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