

The trends and practical look of advanced steel frame structures

Nikolay I. Vatin¹, Tesfaldet H. Gebre^{2*}, Shishay B. Gebreslassie²

¹Peter the Great Saint Petersburg Polytechnic University, 29 Politechnicheskaya St, Saint Petersburg, 195251, Russian Federation

²Peoples' Friendship University of Russia (RUDN University), 6 Miklukho-Maklaya St, Moscow, 117198, Russian Federation

*tesfaldethg@gmail.com

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Abstract

The aim of the work is to present the trend of the advancement of steel design code and practical approach of steel frame design from the current AISC-LFDR to the advanced analysis. As the trend of steel frame analysis method is from first-order elastic analysis to second-order inelastic analysis which is an advanced analysis. **Methods.** In this paper the comparison between the load – displacement curves of several structural analysis methods is presented. Case studies are considered to analyze by different methods and comparison of practical advanced analysis method with PROKON software. The case studies includes a two-story one bay steel frame and four bays of twelve-stories steel frame. The **results** of first-order elastic, elastic buckling, second-order and nonlinear analyses of an unbraced frame are compared and their difference is presents. The proposed software for advanced methods demonstrates the accuracy and the computational efficiency in predicting the nonlinear analysis response of steel frame structures.

Keywords: steel frame analysis, sway frame, nonlinear analysis, advanced analysis

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Introduction

The current design approach under American Institute of Steel Construction (AISC) specifications includes three design methods and the most common and up-to-date approach for steel design is the load and resistance factor design specification (LRFD). On the other hand, the plastic design (PD) approach and the allowable stress design specification (ASD) are quiet used. The aim of steel structure designer is to analyze the structural member of the frame through assessing displacements, internal forces and moments and checking member safety.

Different methods are available for analysis and design of steel frame structures and likewise there are many commercial software packages used in practice which provide a variety of approaches to the problem [1–4]. The steel framed structure behavior is affected by the geometric and material nonlinearities which includes second-order effect and gradual yielding respectively. As the trend of steel frame analysis method is from first-order elastic analysis to second-order inelastic analysis which is an advanced analysis. Elastic structural analysis is developed to calculate the internal forces at each member of the structure, whereas inelastic structural analysis is utilized to predict the ultimate strength of each isolated member [3–5]. The comparison between the load-displacement curves of several structural analysis is shown in Figure 1 because it includes the key factors influencing steel frame behavior. These approaches are well documented by McGuire, Gallagher, and Ziemian (2000) as well as in the individual references cited [6–7].

The purpose of this paper is to present the trend and practical approach of steel frame design from the

Nikolay I. Vatin, D.Sc. (Eng.), Professor, Higher School of Industrial Civil and Road Construction; eLIBRARY SPIN-code: 4386-7789, ORCID iD: <https://orcid.org/0000-0002-1196-8004>.

Tesfaldet Hadgembes Gebre, PhD Student, Department of Civil Engineering, Engineering Academy; ORCID iD: <https://orcid.org/0000-0002-7168-5786>.

Shishay Berhane Gebreslassie, master student, Department of Civil Engineering, Engineering Academy; ORCID iD: <https://orcid.org/0000-0001-5683-829X>.

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current AISC-LFDR to the advanced analysis. The first-order analysis (Elastic analysis) is the most common method as the deflection is limited to a small and the equations of equilibrium are developed with reference to undeformed configuration of the structure as presented in Figure 1. The first-order analysis is not an advanced analysis method as the code ignoring the effect of buckling, yielding and imperfections for example residual stress, crookedness's and twist as they are considered in the advanced analysis [6]. An elastic buckling analysis can provide the critical buckling load of a single column and is the basis for the effective length factor. It can be seen in Figure 1 that the results of this analysis do not provide a load-displacement curve but rather the single value of load at which the structure buckles.

In the AISC LFRD-1993, the second-order $P-\delta$ and $P-\Delta$ effects can be estimated from a first-order analysis by using the respective $B1$ and $B2$ magnification factor to correlate the linear moments to second-order moments based on the results from Kanchanalai (1977) and Bjorhovde et al. (1978). Unlike the first-order analysis, in which the equilibrium and kinematic relationships of a frame are established with respect to the undeformed geometry of the structure, the equations of equilibrium in the second-order analysis are associated with the deformed geometry of the structure [8–9]. The important attributes which affect the behavior of steel framed structures may be grouped into two categories: geometric and material nonlinearities. The geometric nonlinearity includes second-order effects associated with $P-\delta$ and $P-\Delta$ effects and geometric imperfections [10]. The material nonlinearity includes gradual yielding associated with the influence of residual stresses and flexure [11]. Generally two components second-order effects should be included in the analysis. Primarily, when the influence of member curvature is included, it is said that the $P-\delta$ effects or member effects are included, and, secondly, while the side-sway effects are included, it is said that the $P-\Delta$ effects, also referred to as the story sway or frame effects, are included. The load-displacement history obtained through second-order analysis may approach to the critical buckling load obtained from the eigenvalue solution as shown in Figure 1. Second-order analysis usually requires an iterative solution so it is a bit more complex than the first-order elastic analysis [8; 12]. Because of the problems inherent with iterative solutions, many researchers have proposed one-step approximations to the second-order elastic analysis [12]. It should also be noted that not all commercial computer analysis software includes both the member effects and the frame effects.

First-order rigid-plastic analysis neglects the effects of elastic deflections and assumes that all struc-

tural deformation takes place in discrete regions, called plastic hinges, where plasticity has developed. Once a sufficient number of plastic hinges have formed so that the structure will collapse, it is said that a mechanism has formed and no additional load can be placed on the structure. Thus, a plastic-mechanism analysis can predict the collapse load of the structure as shown in Figure 1.

There are two main types of second-order analysis, i.e. second-order elastic analysis and second-order inelastic analysis. The first type does not consider the effect of material yielding therefore section capacity check per member is required to locate the load causing the first plastic moment or first yield moment of the structure [3; 8; 13]. It has a limitation in providing information about non linearity of the structure and excludes the necessity of moment amplification factor. The second type considers the effect of material yielding so the maximum failure load can be directly located by the load deflection plot. The section capacity check is therefore used for assessing the condition of plastic hinge formation [1; 3; 14–18]. Direct second-order inelastic analysis for frame design without the use of K -factor to do member by-member capacity checks with code requirements [3].

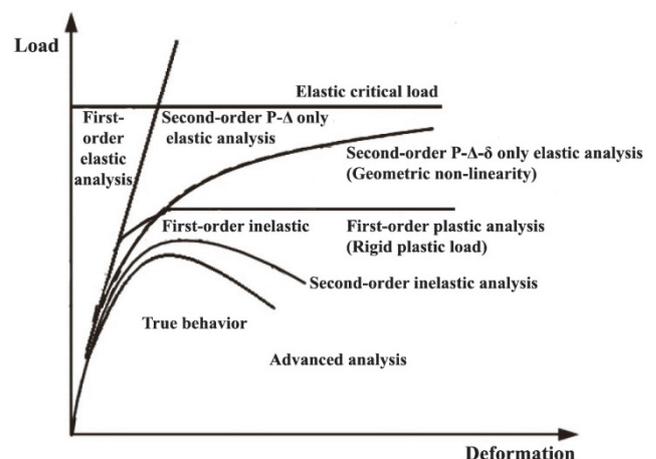


Figure 1. Load-displacement curve for different method of analysis

Advanced analysis is defined as any analysis method that accurately represents the behavioral effects associated with member primary limit states to the extent that corresponding specification checks are superseded [19].

1. Methods and discussion

1.1. Comparison of first-order, elastic buckling and second-order elastic analyses

Figure 2 is considered to show the similarity and difference between the three methods and the analysis is carried out using PROKON (2019) by considering

different cases of deformations. The frame is formed with three W8×28 members subjected to gravity load and a lateral load. The result of the three analysis is presented graphically in Figure 2. As the graph is presented load vs displacement, both first-order and elastic buckling analysis are formed linearly but yielded in different points. The first-order analysis yield as a linear and the elastic buckling analysis yield with a critical load of P_{cr} but both intersects each other at one point. In the case of second-order elastic analysis the approach is done by considering different load steps, the maximum load should be less than P_{cr} thus the lateral displacement increases gradually to a large amount consequently additional moments are developed.

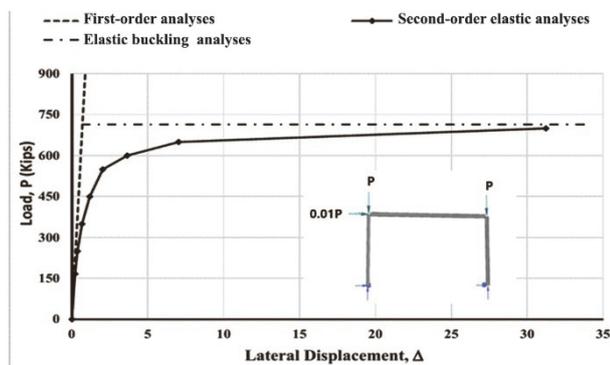


Figure 2. Comparison of load/lateral displacement results for the frame

The frame is loaded with gravity load of P , a lateral load of $0.01P$ and in addition the columns are treated as pin supports. The relationship between displacement and load is shown in Figure 2 as the elastic buckling analysis yields a critical load of 714 Kips with the given frame buckling in a sideways mode. The point of intersection of the first-order and elastic buckling is denoted by the load of 714 Kips and displacement of 0.69 in. The results of the second-order elastic analysis are also shown in Figure 2. This analysis was carried out at eight different load levels. It can be seen that as the magnitude of the load P is increased, the lateral displacement increases at a progressively greater rate. This reflects the influence of the additional moments induced as the structure deflects. As the load approaches 714 Kips, the slope of the load-displacement curve approaches to zero and the displacement tends toward infinity, confirming that a second-order elastic analysis can be used to approximate the results of an elastic buckling analysis.

1.2. Examples 1:

two-story unbraced plane frame analysis

A two-story one bay steel frame is considered and analyzed by different methods as it is tabulated in the table below. Different methods are presented below

which allow us to compare the trend of steel frame analysis as shown in Figure 3. The steel frame is subjected to the combined factored gravity and lateral loads and also considering preliminary member sizes and yield stress of steel $F_y = 50$. The comparison is done by considering the steel frame as sway frame and their results are tabulated in the Table 1.

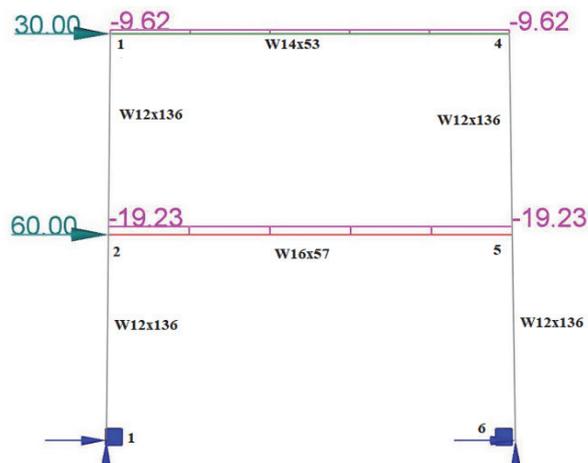


Figure 3. Two-story unbraced frame

Although steel structures can be adequately designed by using the AISC-LRFD method as shown in the previous section, the member capacity checks and the determination of effective length factors and their procedures are often tedious and confusing. Also, since AISC-LRFD method is a member-based design approach, inelastic member forces will not be redistributed and the actual structural behavior and failure mode cannot be predicted.

1.3. Examples 2:

analysis for geometrically nonlinear plane frame

In order to account for the true stiffness of elastic frames in the determination of the effective length factors of their columns a geometrically nonlinear analysis of the frame as a whole is performed using java software [19]. The properties of the frame and a load pattern for the frame are prescribed. The applied load is the product of the load pattern and a load factor. The nonlinear analysis is performed by increasing the load factor stepwise with the constant arc method [10].

The nonlinear governing equations are solved with a stepwise iterative method and controlled by keeping the arc increment constant [20; 21]. The displacement increments in the steps are summed to yield the total displacements. In each step of the analysis, the tangent stiffness matrix K of the current frame configuration is decomposed into the product of a left triangular matrix L with unit diagonal elements, a diagonal matrix D with diagonal coefficients d_i and a right triangular matrix L^T . The product $d_1 d_2 d_3 \dots d_n$ of the diagonal coeffi-

icients of D equals the determinant of the tangent stiffness matrix K of the frame in the current load step.

$$K = LDL^T, \det K = d_1, d_2, d_3, \dots, d_n.$$

Unbraced building frame with hinged and fixed supports is considered for comparison between software for nonlinear analysis with java programming and

PROKON structural analysis and design. The frame given in Figure 4 consists of four bays of equal width 6.0 m and twelve stories of equal height 4.0 m. All girders carry a uniformly distributed load of 80 KN/m. The coordinate origin is located at the foundation of the leftmost column. Axis x is directed horizontally from left to right, axis y vertically from bottom to top.

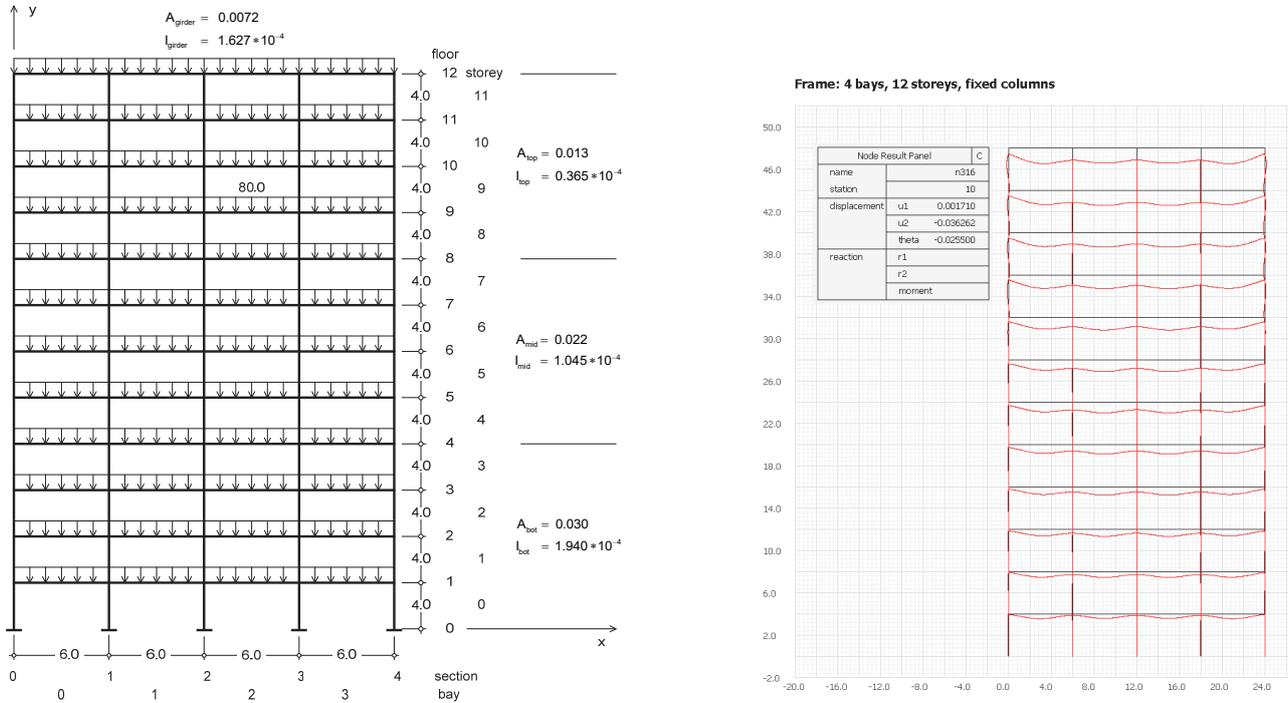


Figure 4. Graphic display with the generated frame, member property and displacement of the frame

Table 1

Comparative result of sway frame using different method of analysis

Members/ nodes with unites	First-order elastic	Elastic buckling	Second-order elastic	First-order vs. second-order (%)	Nonlinear analysis	Second-order elastic vs. nonlinear analysis (%)
M12 (Kipin)	62264.26	—	54416.74	12.60	57321.54	5.07
M23 (Kipin)	81156.09	—	81173.42	0.02	80246.77	1.14
N2/5 (Kipin)	149028.27	—	153159.72	2.77	153536.88	0.25
M25(Mid) (Kipin)	87765	—	80443.00	8.34	79942	0.62
M45 (Kipin)	82782.84	—	86703.16	4.74	85358.65	1.55
M56 (Kipin)	66245.44	—	66456.55	0.32	68178.22	2.59
N3/4 (Kipin)	74561.95	—	79964.77	7.25	78176.09	2.24
M34(Mid) (Kipin)	71508.69	—	87657.9	0.49	69783.60	1.98
N25 (Kip)	342.69	510.60	385.27	12.43	362.29	5.96
N34 (Kip)	1008.64	1502.87	1041.43	3.25	1024.77	1.60
N12 (Kip)	4472.84	6664.53	4416.01	1.27	4425.07	0.21
N23 (Kip)	1490.93	731.4857	1472.41	1.26	1480.8	0.57
N45 (Kip)	1510.51	2250.66	1529.02	1.23	1520.58	0.55
N56 (Kip)	4528.36	6747.26	4585.19	1.25	4573.83	0.25
Δ3 (in)	2.28	—	6.27	175.00	5.76	8.13
Δ2 (in)	0.8	—	2.57	221.25	2.35	8.56
v3 (in)	0.81	—	0.81	0.00	0.86	6.17
v2 (in)	0.61	—	0.61	0.00	0.63	3.28

2. Result and discussion

The results of comparative steel frame analysis using first-order elastic, elastic buckling, second-order and nonlinear analyses of an unbraced frame are given in Table 2. By ignoring all second-order moments, first-order elastic analysis calculates the linear behavior of steel frame. The second-order analysis result may be used to approximate using elastic buckling analysis of member axial force. For the frame of Figure 3,

the second-order sway deflections are about 8% larger than those of the second-order analysis, while the moment at the top of the right-hand lower story column is about 12.6% larger than that of the first-order analysis. The nonlinear sway deflections are about 175% larger than those of the first-order analysis, while the moment at the top of the right-hand lower story column is about 5.07% larger than that of the second-order analysis.

Table 2

Comparison result of java software for nonlinear analysis and PROKON software

Members/nodes	Unites	Method of analysis for pinned support		Method of analysis for fixed support	
		PROKON	Java software	PROKON	Java software
Vertica displacement top left node	mm	14.04	14.2	35.7	36.3
Vertica displacement top middle nodes	mm	32.80	30	76.06	76.4
Mid span moment for top story	kNm	128.20	130	431	430
End moments for top story	kNm	248.52	240	576.52	578

The unbraced building frame in Figure 4 is analyzed with hinged and fixed supports using software for nonlinear analysis with java programming. The load pattern is applied in 10 steps. The pinned and fixed support frame reaches a singular state for load factors 0.9628 and 2.4412 respectively. The displacement of the frame in the singular state is shown in Figure 3 and the results for displacement and bending moments using java software for nonlinear analysis and PROKON software are presented in Table 2.

In this example we checked the developed practical advanced analysis software which can be used for nonlinear inelastic analysis of steel frame structures. Referencing the numerical example, the proposed software demonstrates the accuracy and the computational efficiency in predicting the nonlinear analysis response of steel frame structures. It can be concluded that the proposed software and the comparison with other software's show the reliable and valuable for application in engineering design.

Conclusion

As the trend of the frame analysis and design is from hand calculation approach based on member capacity checks to computer-based approach based on advanced analysis to consider the interdependent effects between member and frame stability. Both first-order and elastic buckling analysis are formed linearly but yielded in different points but in second-order analysis the maximum load should be less than P_{cr} thus the lateral displacement increases gradually to a large amount consequently additional moments are developed.

According AISC, the term advanced analysis strictly means second-order inelastic analysis for frame design

without the use of the effective length factor (K -factor). Elastic structural analysis is developed to calculate the internal forces at each member of the structure, whereas inelastic structural analysis is utilized to predict the ultimate strength of each isolated member. The software demonstrates the computational efficiency in predicting the nonlinear analysis response of steel frame structures and the comparison with other software's show the reliable and valuable for application in engineering design. In order to achieve its full potential as a tool for the practical design of steel frames, the upcoming work required in order to take part of the 3D member behavior and member stability analysis with advance analysis.

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НАУЧНАЯ СТАТЬЯ

Тенденции и практический вид современных стальных каркасных конструкций

Н.И. Ватин¹, Т.Х. Гебре^{2*}, Ш.Б. Гебресслассие²

¹Санкт-Петербургский политехнический университет Петра Великого, Российская Федерация, 195251, Санкт-Петербург, ул. Политехническая, 29

²Российский университет дружбы народов, Российская Федерация, 117198, Москва, ул. Миклухо-Маклая, 6
*tesfaldethg@gmail.com

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Аннотация

Цель исследования – изучить тенденцию развития строительных норм по стальным конструкциям и практического подхода к проектированию стальных каркасов от ныне действующих стандартов Американского института стальных конструкций до расчетов по методам более высокого порядка, поскольку развитие теории расчета стальных конструкций заключается в переходе от упруго-линейного расчета первого порядка к нелинейному расчету второго порядка. **Методы.** В работе представлено сравнение зависимостей нагрузки от перемещения, полученных по различным теориям расчета. Проводятся расчет конкретных примеров конструкций различными методами и сопоставление практического метода высокого порядка с программой PROKON. Конкретные примеры включают в себя двухэтажную однопролетную стальную раму и двенадцатиэтажную четырехпролетную раму. **Результаты.** Выполнено сравнение результатов упруго-линейного расчета первого порядка, расчета устойчивости по упругой схеме, расчета второго порядка и нелинейного расчета стальных рам и показано их различие. Предложенное программное обеспечение для расчета по методам высокого порядка демонстрирует точность и вычислительную эффективность в определении нелинейного поведения стальных конструкций.

Ключевые слова: расчет стальных рам, рамы с поперечным смещением, нелинейный расчет, расчет высокого порядка

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Ватин Николай Иванович, доктор технических наук, профессор высшей школы промышленно-гражданского и дорожного строительства; eLIBRARY SPIN-код: 4386-7789, ORCID iD: <https://orcid.org/0000-0002-1196-8004>.

Гебре Тесфалдет Хадзембес, аспирант, департамент строительства, Инженерная академия; ORCID iD: <https://orcid.org/0000-0002-7168-5786>.

Гебресслассие Шишай Берхане, магистрант, департамент строительства, Инженерная академия; ORCID iD: <https://orcid.org/0000-0001-5683-829X>.