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Properties and improvement directions of software of single-storey buildings with frame structures

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The main stages of creating a spatial model of the steel frame are considered for industrial buildings or warehouses with a pitched roof. Different approaches to the analysis of internal forces of the first and second orders and the stability calculation for steel elements of building structures under the combined action of compression and transverse bending are highlighted using software applications. Ways to improve the process of creating a calculation model, design documentation, and working drawings are outlined. A comparison of specialized software products for calculating building models with portal frames (Autodesk Robot Structural Analysis Professional, PortalPlus, Consteel, Tekla Structural Designer, and Dlubal RFEM) is presented. Their advantages and disadvantages are indicated

Keywords: software, spatial model, portal frame, buckling, restraint

Властивості та напрями вдосконалення програмного забезпечення для розрахунку одноповерхових будівель з рамними конструкціями

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Розглянуто основні етапи створення просторової моделі сталевого каркаса для промислових будівель або складів зі скатною покрівлею. Висвітлено різні підходи до проведення аналізу внутрішніх зусиль першого та другого порядків і виконання розрахунку стійкості сталевих елементів будівельних конструкцій при сумісній дії стиску й поперечного згину із застосуванням прикладних засобів програмного забезпечення. Намічено шляхи вдосконалення процесу створення розрахункової моделі, проєктної документації та робочих креслень. Наведено порівняння спеціалізованих програмних продуктів для розрахунку моделей будівель із портальними рамами (Autodesk Robot Structural Analysis Professional, PortalPlus, Consteel, Tekla Structural Designer і Dlubal RFEM), указано їхні переваги та недоліки. Встановлено, що для збільшення точності розрахунків і наближення їх до дійсних умов роботи конструкції внутрішні зусилля потрібно визначати в просторовій моделі за нелінійною теорією другого порядку. У процесі обчислення коефіцієнта стійкості при згині доцільно врахувати крутильну або крутильну та зсувну жорсткість конструкцій, що розкріплюють стиснутий пояс елементів, схильних до втрати стійкості. Зокрема, хрестові в’язі частково сприймають, розподіляють і передають на основу горизонтальні навантаження на будівлю. Крім цього, вони забезпечують просторову жорсткість будівлі та слугують для розкріплення і зменшення розрахункової довжини елементів рами. В’язі можуть не тільки виконувати свою безпосередню функцію, але й ефективно використовуватися для розкріплення сталевих елементів з метою уникнення втрати стійкості, таким чином зменшуючи ступінь використання перерізу і витрати сталі. Розглянуто конструктивні заходи для усунення явища втрати просторової стійкості лінійних елементів поперечної рами каркаса будівлі при сумісній дії стиску, поперечного згину та кручення. Приєднані до елемента різного роду другорядні конструкції, в тому числі встановлені планомірно, збільшують його жорсткість і перешкоджають деформуванню. Проаналізовано вплив розкріплення на несучу здатність

Ключові слова: програмне забезпечення, просторова модель, портальна рама, втрата стійкості, розкріплення

Introduction

Conventional mathematical models do not characterize all the behavior features of the frame structure in the building framework, especially with significant rigidity of the connected elements. In such cases, the simulation often has little in common with the actual processes, does not correspond to the real picture of the stress-strain state, and needs refinement to adequately reflect the using degree of the cross-section by stress required to ensure the reliability of the structure as a whole. To increase the accuracy of calculations and bring them closer to the actual operating conditions of the structure, the internal forces must be determined in a spatial model by a nonlinear theory of the second order. It takes into account the geometric nonlinearity and is essentially the calculation of the deformed scheme, in which the equilibrium equations are written for the deformed state of the system. By buckling from compression, bending and torsion in the vertical or inclined element of the portal frame, which acts as a beam-column in a complex stress-strain state, several deformations occur simultaneously. The spatial deformed state of the rod consists of the angle of rotation around the longitudinal axis, as well as displacements in the direction of the horizontal axis y and vertical axis z in cross-section, respectively (curvature and deflection).

Review of the research sources and publications

The transverse frames linear elements stability issue taking into account all possible factors, in the spatial setting for different types of loads, boundary conditions, and cross-sections is already practically solved in scientific and technical schools of Western Europe at the level of theory, rationing and programming. Issues of operation and behavior of thin-walled load-bearing elements of frame structures under complex loads are covered in great detail. So, the articles [1 – 4] are devoted to the advanced design and geometrical optimization of steel portal frames. The papers [5, 6] present the influence of the diaphragm effect on the behavior of pitched roof portal frames. The purpose of the research is to make a comparison between the simplified design model of a portal frame, where the supports simulating the purlins are considered with infinite axial rigidity, and a portal frame design model where the calculated stiffness of the cladding for the lateral supports is introduced manually. The approbation of the second-order theory in the works [7, 8] demonstrates that insufficient restrained structure in an elastic stage is very sensitive to the load and curvature change, therefore, by determining the bearing capacity consideration of braces rigidity possibly will be effective.

Definition of unsolved aspects of the problem

Not solved before a part of the problem is the allocation of those points, to which need to pay special attention by the analysis, design, and calculation of portal frames for built model compliance with real work of structures at complex resistance. As a research task, it was decided to compare different software products for the design of the structures.

Problem statement

We will analyse and identify ways to solve the problem of determining the load-bearing capacity of steel beams and columns, which are part of the portal frames and prone to loss of overall (spatial) stability, as well as the problem of expanding options and improving the design of single-storey buildings.

Basic material and results

The tendency of the element to instability arises due to its considerable flexibility and insufficient fastening of the compressed flange by attached structures, which include: monolithic and prefabricated reinforced concrete slabs; steel flat and profiled flooring, sandwich panels and other enclosing structures; girders, purlins, floor beams, and other secondary beams; discrete bracings (horizontal cross bracings, strands). The first two types of structures can be attributed to continuous bracings, the other two belong to discrete ones. These structures reduce the calculated effective length of the beam and increase its overall stability. In construction, thin-walled structures that work in conjunction with the load-bearing flooring are widely used. For coatings of industrial and civil frame buildings due to high-efficiency light roofs are often used, consisting of purlins, which can support on the main beams (rafters) on top or adjacent to them at the same level, and steel profiled sheet, the rigidity of which when fixed to the upper flange is used to increase the stability and fixing of the beams from twisting. Also, the stabilization of the beams can be done through the arrangement of structural parts: rafter stays, flat and three-dimensional stiffeners, protrusions of the beams in the supporting areas, and the adjacency to the columns in the supports. Where the compressive flange is not laterally supported, additional elements should be provided to ensure a torsional or lateral restraint in selected cross-sections of the rafter. Such elements could be inclined bars (rafter stays) connecting the compressive flange with the purlins or longitudinal bars anchored at rigid parts of the overall structure.

To check the stability of the steel element, it was decided to determine the stresses in the compressed flange and compare them with critical ones, which were equal to the calculated resistance of steel (yield strength) multiplied by the stability factor, which depends on the design scheme, geometric cross-sectional properties, and distance between points of compressed flange restraining. To determine the conditional flexibility for lateral-torsional buckling, depending on which the decreasing coefficient of bending stability is set according to European standards, it is necessary to know the elastic critical moment for lateral-torsional buckling. Its value for the I-beam hinged at the ends, loaded with an evenly distributed load, can be set following building codes. In other cases, it is recommended to quantify the critical moment by simulation. For a rod hinged at the ends, loaded with an evenly distributed load and reference bending moments, there is a method of determining the critical moment. Under such conditions and different boundary conditions and types of loads, it is recommended to use a special free LTBeam program. A critical moment is required to calculate the insufficiently restrained bending steel I-elements by the lateral-torsional buckling. In addition, it is sometimes advisable to take into account the rotational or rotational and shear stiffness of structures that discretely or continuously restrain the compressed flange of the beam in most practical cases and reduce the deformation of its displacement. Taking into account the rounding at the junction of the flange to the web allows you to significantly increase the value of the torsional constant required for calculations. It can also be identified in this common computer program.

Taking into account the main factors that characterize the special operating conditions of the steel rod element with complex resistance and providing spatial stability for reliable operation of the structure without failures due to detailed analysis, allows you to more accurately determine the value of internal forces. This affects the overall stress-strain state of the structure and determines the calculated ratio of normal stresses, and therefore has a positive effect on the level of use and strength of the material.

In particular, the cross bracings partially receive, distribute and transmit the horizontal loads on the building pavement. Besides, they provide the spatial rigidity of the building and serve to secure and reduce the effective length of the frame elements. Bracings can not only perform their direct function but can also be used effectively to restrain steel elements to avoid loss of stability, thus reducing the use of cross-section and steel consumption.

The process of creating a calculated schematic model of a single-storey building should, taking into account the current state of development of computer technology, describe in as much detail, accurately, and conveniently as possible the structural relationships between the various elements of the building system. The process should include the following basic steps, maintaining a balance between structuring, the speed of obtaining the final results through automation, and ease of use (for example, testing the Frame Generator Autodesk Robot Structural Analysis Professional 2021). When creating steps and spans of load-bearing elements of the building in the window of the Frame Generator, which is the first stage of modeling, the number of structural elements in the transverse and longitudinal directions is indicated. If necessary, it is possible to create a geometric grid of complex shapes. In the next step, the geometry of the roof (flat, one- or two-slope), the size of the transverse frame, the type of supports (hinge, rigid clamping), cross-sections of columns and beams, steel grade are described. When choosing the type of rafter and its design, not all outline schemes are specified. In particular, the scheme with a puff (tied portal frame), the scheme with welded rafter and column cross-sections with linearly variable height, or, the curvilinear scheme (curved rafter portal frame) is not presented. These schemes are shown in Figure 1.

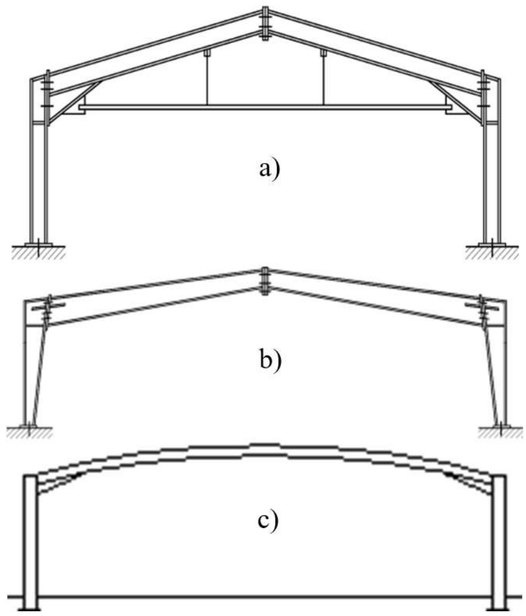

Figure 1 – Restraining points between bracings and buckling coefficients definition

In a tied portal frame (Figure 1,a) the horizontal movement of the eaves and the bending moments in the columns and rafters are reduced. A tie may be useful to limit spread in a crane-supporting structure. The high axial forces introduced in the frame when a tie is used necessitate the use of second-order software when analysing this frame form.

Large spans over 30 m can also be overlapped with solid-wall frames. For such large hall dimensions, completely welded construction is shown in Figure 1,b. The welding of two flanges sheets and a web sheet for rafter and column cross-sections with linearly variable height is done using automatic welding machines, the fillet welds with larger length can produce economically. The high, slender webs of the welded I-section are prone to buckling, so buckling stiffeners may be required, as for the welded structures used in bridge construction.

Portal frames may be constructed using curved rafters (Figure 1,c), mainly for architectural reasons. Because of transport limitations, rafters longer than 20 m may require splices, which should be carefully detailed for architectural reasons.

The curved member is often modelled for analysis as a series of straight elements. Alternatively, the rafter can be fabricated as a series of straight elements. It will be necessary to provide purlin cleats of varying heights to achieve the curved external profile.

Next is the process of creating sections, grids, chords for through rafter (braces, racks, support braces). It is also necessary to cover the floor slabs (if any, their type, location, size of beams, columns, supports, slab cross-section of reinforced concrete platform). Eaves, cantilevers, and roof parapets are described by size, location, cross-sections. Creation of haunches between a column and a beam, haunch of beams in a roof ridge provides types of cross-sections, the sizes (height and width). Next is the design of the purlins: their number, deviations from the edges and the middle of the span, the type of scheme (single, continuous), the rafter stays, puffs. But the rafter stays are not reflected in the model and therefore do not have a geometric description. Layouts of vertical bracings and bracings on the roof require more detail, as well as the scheme of the outer wall (columns, beams, bracings can be in different variations).

During initial design, the rafter members are normally selected according to their cross-sectional resistance to bending moment and axial force. In later design stages stability against buckling needs to be verified and restraints positioned attentively.

The buckling resistance is likely to be more significant in the selection of column size, as there is usually less freedom to position rails to suit the design requirements; rail position may be dictated by doors or windows in the elevation.

If introducing intermediate lateral restraints to the column is not possible, the buckling resistance will determine the initial cross-section size selection. It is therefore essential to recognise at this early stage if the side rails may be used to provide restraint to the columns. Only continuous side rails are effective in providing restraint. For example, side rails interrupted by roller shutter doors, cannot be relied on as providing adequate restraint.

Where the compression flange of the rafter or column is not restrained by purlins and side rails, restraint can be provided at specified locations by column and the rafter stays to the inside flange (Fig. 2).

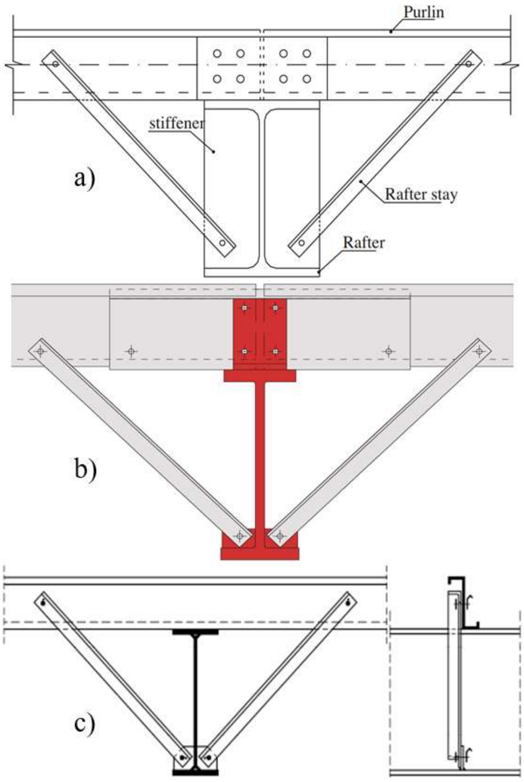

Figure 2 – Torsional restraint of a rafter with a lower flange under compression through rafter-stays

a – with stiffeners; b, c – with short local connectors

Purlins attached to the top flange of the rafter provide stability to the member in several ways: direct lateral restraint, when the outer flange is in compression; intermediate lateral restraint to the tension flange between torsional restraints, when the outer flange is in tension; torsional and lateral restraint to the rafter when the purlin is attached to the tension flange and used in conjunction with rafter stays to the compression flange. Initially, the out-of-plane checks are completed to ensure that the restraints are located at appropriate positions and spacing. Unfortunately, the restraining points are not set automatically (Fig. 3) after creating a model in the Frame Generator, which requires additional time.

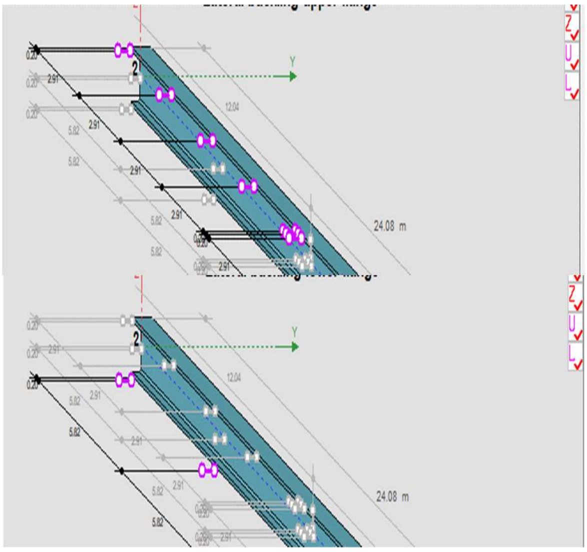

Figure 3 – Restraining points between bracings and buckling coefficients definition

Although efficient portal frame analysis and design will use special software, which is likely to be using elastic-plastic analysis, initial manual elastic analysis is simple. In most circumstances, a reasonable estimate of the maximum bending moments will be obtained by considering only the vertical loads. Appropriate cross-sections can then be chosen based on this analysis. For the initial analysis, it is common to assume that the second moment of area of the column is 1,5 times that of the rafter section. For the pinned base frame, the bending moments at the eaves and apex can be calculated following [9, 10].

It is probably that many portal frames will be sensitive to second-order effects, which are likely to increase the design moments by up to 15%. If undertaking a preliminary analysis, bending moments from a first-order analysis should be amplified to allow for these effects. Calculation of boundary conditions, verification, and selection of cross-sections include stability testing by EN 1993-1-1. Loads in the Frame Generator can be constant, variable, crane, meteorological. The parameters of wind and snow include speed, pressure, terrain, unexpected precipitation. Explanatory notes, drawings, spatial view of the main components (with joints) are generated automatically (Fig. 4) but require some refinement and adjustment manually.

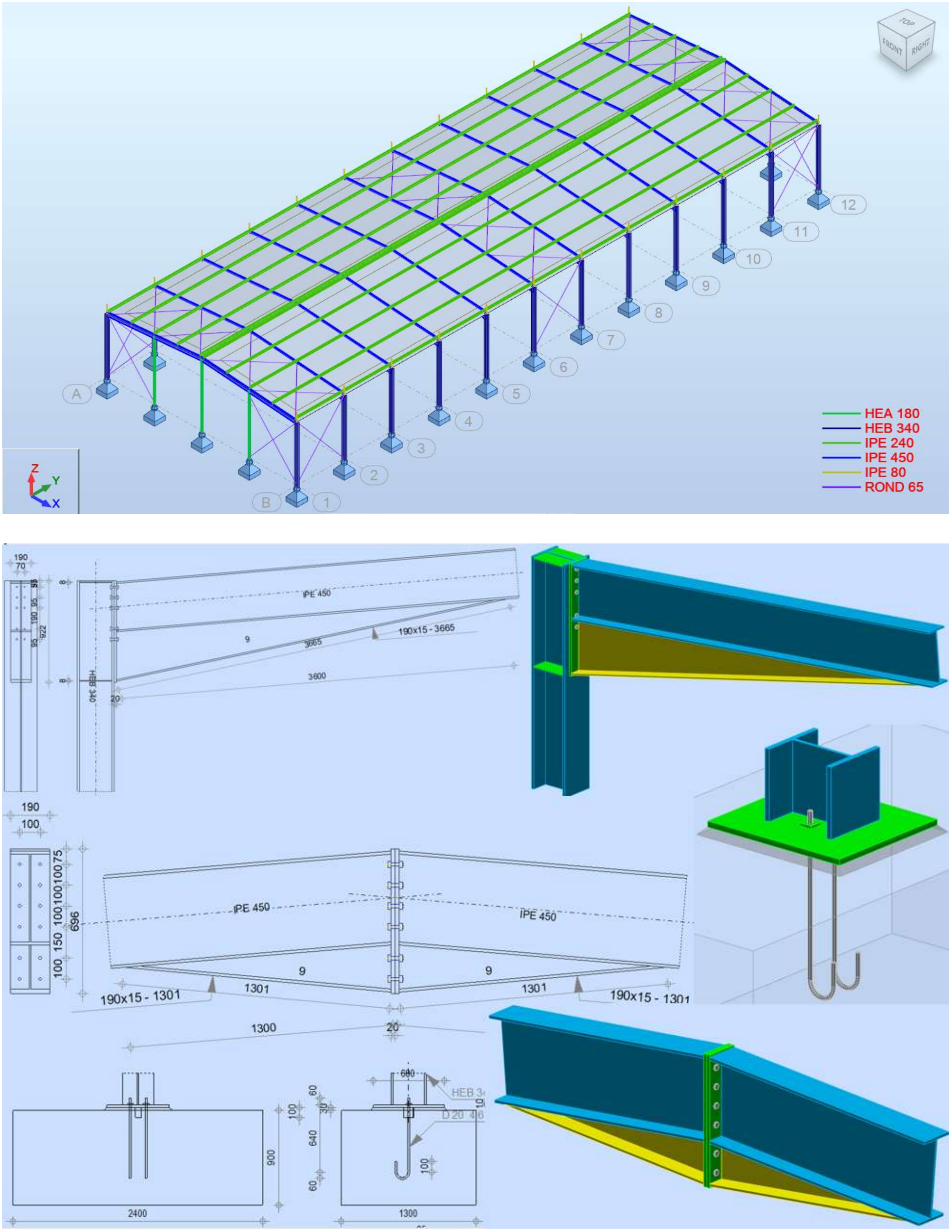

Figure 4 – Design model of the building framework;
drawings, spatial view of the main bolted and welded joints

Let's compare different software for the portal frame design. Advantages of Autodesk Robot Structural Analysis Professional [11] are next:

- automation and speed of model creation;
- the Frame Generator with a user-friendly interface;
- integration with other products.

Disadvantages of Autodesk Robot:

- the need to refine the model;
- sharpening under reinforced concrete structures;
- simplified export to Advance Steel.

Advantages of Consteel, Tekla Structural Designer, and Dlubal RFEM:

- accuracy, versatility and systematization;
- profile for steel structures;
- the ability to create drawings (Tekla SD);
- the ability to consider the bracings stiffness and design of composite structures (Consteel and RFEM).

Disadvantages of Consteel, Tekla SD and RFEM:

- the difficulty of development due to the versatility;
- cost, limited area of application;
- no frame generator and long calculation (Consteel).

Advantages of PortalPlus [12]:

- quick calculation with details;
- clarity of presentation;
- lightness and free distribution.

Disadvantages of PortalPlus:

- no bracings;
- approximate definition of internal efforts;
- the limited scope of use and no guarantee.

Conclusions

By the design of portal frames it can use the indicative data for parameter values:

- portal frame span: 20 – 50 m;
- portal frame step: 5 – 7,5 m;
- roof slope: 6° – 10°;
- construction height of solid-wall rafter: 1/25 – 1/45 of span;
- construction height of through rafter: 1/18 – 1/40 of span;
- ratio of column height to span: 1/4 – 1/7;
- column weight: 1,5 – 2 of rafter weight;
- length of the haunch area: 10% of span;
- height of the haunch: 2 rafter heights;
- step of purlins: 1,5-3 m.

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