



Research paper

The use of the bioinspired nodes with a variable center of rotation to optimize the moments in a portal frame

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Abstract: This publication shows an algorithm for the design of a fully new ridge node in a steel, portal frame with a variable center of the rotation for the girders connected to it. The mechanics of the node was inspired by the mechanics of a bending movement of the human knee joint, due to a variable center of its rotation. This innovative structure of the ridge node can be optimized by any objective function that is based on the bending moments, occurring in the portal frame, for any chosen type of loads or their combinations. The proposed algorithm is presented using two specific examples of the portal frame for two, completely different objective functions. The results for both examples were compared to the benchmark model with a classic connection in the ridge, using an engineering program using finite elements analysis. The whole work was concluded by showing the results and potential directions for further development of such new technology.

Keywords: bioinspired node, optimization, portal frame, steel structure

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1. Introduction

1.1. Portal frames and their connections

Portal frames are the most frequently used solution for steel halls. Depending on the structure of individual nodes, the connections can be considered as pinned or rigid, in which stiffness of the rotation can be determined using vary algorithms [1]. Mechanical characteristics of nodes have crucial meaning for the distribution of the internal forces in the frame [2].

Constructions such as portal frames work in a wide and variable range of the stress: depending on the direction of the wind or the snow, the values of the bending moments in certain nodes change in a radical way, changing not only its value but also the sign [3]. In the ridge node of the frame, the theoretical center of mutual rotation of the girders most often covers the intersection point of their axis and in each case is located nearby this connection [4].

1.2. Motivation and inspiration

The main motivation was bionics in civil engineering. This concept is highly utilized nowadays due to novel configurations [5]. Main sources of inspiration was the mechanics of the human knee while flexing [6, 7]. In its first phases, the cartilage of the femur bone in the knee joint is rolling and then it is slightly sliding [8]. Thus, the movement range is wider than in other human joints [9]. It is presented on a graph in Fig. 1. It is a displacement of a point in the femur bone (red dot with local coordinate system YZ) [10]. The rotation and the shift means that there is a center of mutual rotation of that is not in the same location as the center point only for the rotation. It means that this point is outside of the node. In biological system, this joint arrangement is especially beneficial due to an expansion of the range of bending knee movement. For structural systems in structures, this solution introduces an additional parameter (variable center of rotation) that can be utilized in a process of optimization.

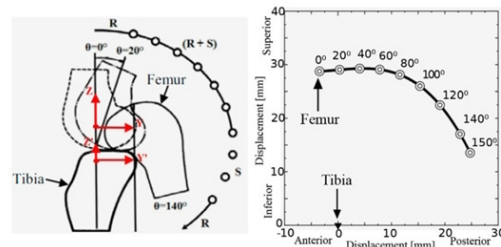


Fig. 1. Displacement of a femur in the human knee with respect to the flexion angle

1.3. Aim and scope

In this paper, there has been offered a fully innovative, different from the classic rigid or pinned connections, structure of the node in the ridge that has two different locations of the center of mutual rotation between girders connected to it. They can be situated far

from the intersection point of the girders' axis. Depending on the external loads, the system automatically adopts the center of rotation in the first or the second location. That leads to minimizing internal forces and thus allows for a more optimal design.

The aim of the paper is to also present the structure and the mechanics of such connection. Moreover, to show the analysis of possibilities to use such idea for different types of optimizations of the distribution of the internal forces in the whole frame.

The publication includes an analysis of a simply supported portal frame. The analysis of the impact of the external loads was simplified to the classic cases from the Eurocodes including self-weight, snow on the roof and wind on the sides of the steel hall. The structure and the way of working of such type of the node in the ridge were shown in two cases of the objective function. Finally, this innovative design was used in the steel hall and was compared to the benchmark model with the same loads but with a classic, pinned node connection in the ridge.

2. The node in the ridge with a variable center of the mutual rotation of the girders

2.1. Proposed solution to the problem

The proposed solution is a bio-inspired node that is located in the ridge of a portal frame. A degree of static determinacy (n) for this structure is based on a Eq. (2.1) [11]:

$$(2.1) \quad n = r + 3z - p - 3 = 4 + 0 - 1 - 3 = 0$$

where: r – number of support reactions, z – number of enclosed areas, p – number of hinged nodes.

For this instance, the degree of static determinacy is equal to 0, thus the structure is statically determined. The analysis in this paper is mainly based on a 2D system. The frame with bioinspired node is assumed to be stiffened out of plane by purlins and bracings. It is assumed that the frame has pinned supports and has a static scheme as shown in Fig. 2.

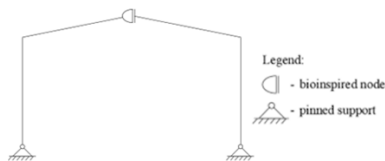


Fig. 2. Static scheme of a portal frame with a bioinspired node in the ridge

The main idea of the node is that two roof girders are connected by three bars that are pinned on both ends. (Fig. 3) A bar in the middle is stiff and vertical, whereas two bars on its left and right side are tie-rods, which are cable-like. They are designed to only resist tensile forces and do not react to compression. The most important aspect in the node is the position of the bars. Axes of the cable bars intersect with an axis of the stiff one above/beneath the node. Both of the intersection points are on the symmetry axis of a frame. In the next part, there is explained an algorithm that is used to find those points, where axes must cross.

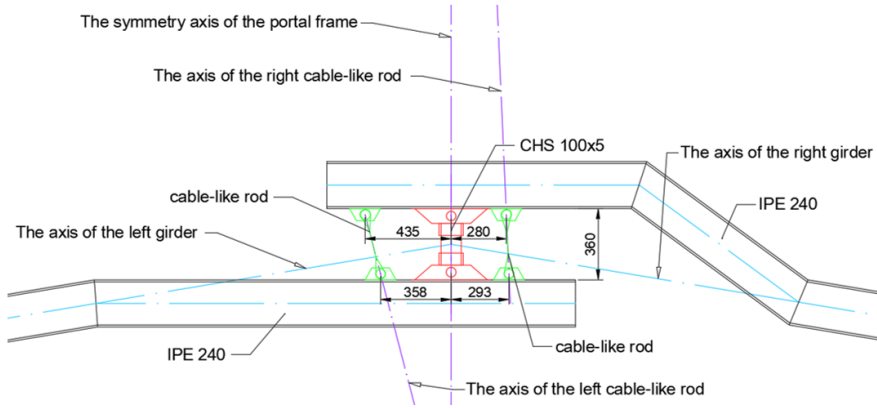


Fig. 3. The proposed design of the bioinspired node

2.2. The designing procedure of the node

Firstly, to find locations of new centers of rotation, there must be implied the Cartesian coordinate system, in which there will be defined an area of the search Ω . (Fig. 4) In this coordinate system, the portal frame is considered with the node in the ridge, which is articulated, but the center of mutual rotation of the girders do not overlays the intersection point of the girder's symmetry. Let the measurements of Ω be defined by the height of the columns, the height of the frame in the ridge and the width of it.

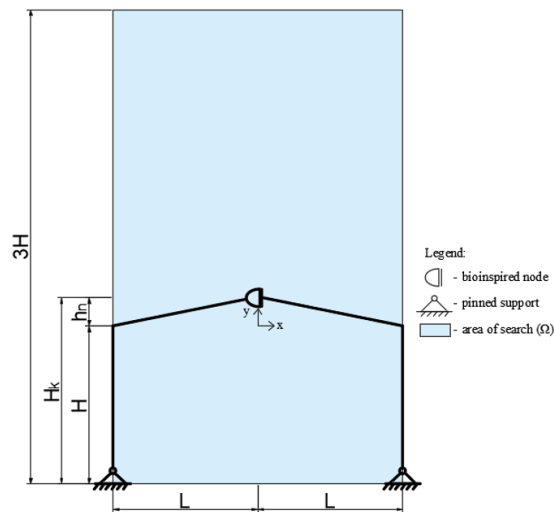


Fig. 4. The area of the search for the centers of rotation

For such defined geometry of the frame, the designing procedure of the node is as follows:

1. Let there be the external loads acting on the construction – Q . In general, it can be any number of the loads acting independently and in any directions. Let there be defined the objective function for the optimization issue $F(Q_i, x_0, y_0)$. It can be defined in any way, based on the internal forces, stress or the displacement occurring globally in the frame or locally in any chosen cross-section.
2. Let there be a numeric grid of the points defined by the spatial step of the calculations $\Delta = (\Delta x, \Delta y)$ and the range of possible locations of the searched center of the node's rotation. Analyzed range and precision of the calculations based on the spatial step are assumed freely according to the needs. The advised area is at least $x_0 \in (-L, L)$, $y_0 \in (-H, H)$, where H is the height of the columns and L is a half of the frame's width.
3. For such defined discretized search area there must be found the values of the objective function $F(Q_i, x_0, y_0)$ for each analyzed load Q_i and each point belonging to the analyzed numeric range. Let there be also determined the values of the bending moment in the node in the ridge $M(Q_i, x_0, y_0)$ and a function $G(Q_i, x_0, y_0)$, which represents a sign of bending moment in each point for each load in Eq. (2.2):

$$(2.2) \quad G(Q_i, x_0, y_0) = \begin{cases} 1 & \text{when } M(Q_i, x_0, y_0) \geq 0 \\ -1 & \text{when } M(Q_i, x_0, y_0) < 0 \end{cases}$$

The values of the function $G(Q_i, x_0, y_0)$ are analyzed for each case of the load and each point belonging to the analyzed numeric range.

4. Every load Q_i is assigned to one of the two groups Q^+ or Q^- , depending on the function $G(Q_i, x_{\min}, y_{\min})$ value, where (x_{\min}, y_{\min}) are the coordinates of the point (x_0, y_0) , for which the objective function $F(Q_i, x_0, y_0)$ adopts the minimal values.
5. In the area of either of the two groups of the loads, independently for Q^+ and for Q^- there is chosen a point, where the objective function $F(Q_i, x_0, y_0)$ for each $Q_i \in Q^+$ or $Q_i \in Q^-$ adopts the minimal value. Depending on the loads chosen for the analysis and on the definition of the objective function, the point can be determined explicitly and in a rigorous way, it will be possible to determine its location, or its assumption will mean the approximated fulfillment of the criteria of the function's $F(Q_i, x_0, y_0)$ minimum.
6. After finding two independent location points of the rotation center of the node in the ridge – adequately (x_0^+, y_0^+) and (x_0^-, y_0^-) minimalizing the objective function $F(Q_i, x_0, y_0)$, it is to be designed its detailed construction solution. For the first example – of an objective function being a maximum moment in the frame – it is possible to derive the formulas using the basics of structural mechanics – the equilibrium equations for the internal forces thus there have been derived two formulas: the first one for a distance between an intersection point of the girders' axes and the rotation center above the ridge node; and the second one for the distance between an intersection point of the girders' axes and the rotation center under the ridge node (2.4), using the Eq. (2.3) and Eq. (2.4) given below adequately for the distance on the Y axis between the ridge node and the center under or over the node:

$$(2.3) \quad y_0^+ = \left(\frac{1}{2} - \frac{\sqrt{3}}{4} \right) H + (H_K - H)$$

$$(2.4) \quad y_0^- = -\frac{2(H_K - H)}{3} - \frac{H}{9} + \frac{1}{9}\sqrt{49(H_K - H)H + 64H^2}$$

where: H – the height of the columns' ends, H_K – the height of the ridge.

7. After the design is done, there ought to be analyzed the correctness of the whole optimization process of the chosen objective function, e.g. by putting in the whole portal frame structure with the detailed structure of the node in the ridge to any structural analysis program of the finite element method and thereafter imply the loads, find the internal forces and examine if, consequently, in each case of the load the objective function assumes the minimal value.

3. Used numerical tools

3.1. A tool to create algorithm for designing procedure – Dynamo

Dynamo, a parametric design tool, was used in the early stages of the analysis. Its key feature was the ability to create loops, allowing for iterative analysis of input parameters and exporting results to text files. This was crucial in designing the node in the ridge.

A Python script in Dynamo was developed to model the frame geometry, using input parameters such as ridge height, column height, offsets, and load conditions, including direction and pressure forces. The most critical input was the center of mutual rotation between the girders, which influenced the calculation of support reactions and cross-section forces: axial, transverse, and bending moments in both columns and girders.

The script iterated through different positions of the rotation center within a defined range, allowing moment values to be determined for any cross-section. The output consisted of two text files: one containing coordinates and moment values at the ridge node on the portal frame's symmetry axis, and another storing objective function values for these coordinates.

3.2. A tool for graphic analysis – Autodesk Civil 3D

Program Autodesk Civil 3D was used for a detailed analysis of the output. In this paper it was used in an unusual way to process, visualize, and analyze the output data from the Dynamo program. Autodesk Civil 3D allows an import of the text files and creating hypsometric maps, based on the imported files. Additional functions were used to create lines by best fit using least squares method, but also to create sophisticated coloristic maps.

Within the framework of this paper, for every analyzed external load, every type of the objective function and every analyzed geometry of the portal frame, there were imported two text files to Autodesk Civil 3D, received from the Dynamo calculations. The file including the values of the objective function was visualized using a hypsometric model. It allowed to find location and the area of the minimalization of this function. Whereas the file including the values of the moment in the node in the ridge was visualized using an analysis of colored map. Then, there were put together results of the analysis for different types of external loads and to choose best fitting points representing the center of mutual rotation of girders that fulfill the criteria.

3.3. A tool for FEM calculations – Autodesk Robot Structural Analysis

The final computer program used for the analysis was Autodesk Robot Structural Analysis. It is a program based on the finite element method. In this research, there were used: a 2D frame elements having 3 degrees of freedom in the node and a 3D steel hall using 6 degrees of freedom in the node. In the 3D model, there were used 3 such portal frames connected by the truss-like elements with 3 degrees of freedom. An additional practicality of the program allowed to make tie-rods only carrying extension forces.

The work in the Autodesk Robot Structural Analysis was the last step in the design of the node in the ridge. It was possible to verify the final results – the values of the moments for every set of loads and compare it with the values received from classic models of the connection in the ridge.

4. The first example of the objective function – the maximum moment in a whole portal frame

4.1. The 2D model of a frame

In this part, there is presented a use of algorithm from section 2.2. to find center of rotation. Beforehand, there was determined a portal frame used for this example. It has 5.0 meters high columns made of HEB 260 and girders made of IPE 240 that take 6.0 meters horizontally on each side of the node in the ridge. The ridge is 1.0 meter above the level of the ends of frame’s columns. (Fig. 5) It has pinned supports. There is a defined Cartesian coordinate system as in the procedure (see section 2.2). The Y axis is on the symmetry axis of the frame and the center of the coordinate system XY that is on the level of the ends of the columns.

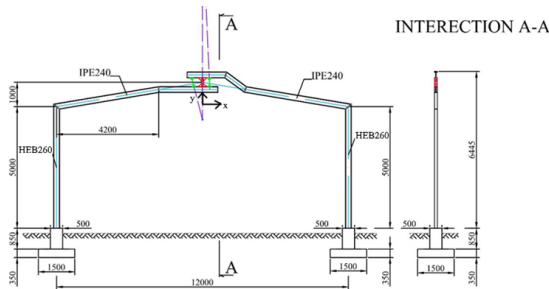


Fig. 5. The geometry of a portal frame used in the first example

There are applying 4 simple load cases The first case of the load Q_1 is the pressure of the wind on the left column (5 kN/m) the second one Q_2 is the pressure of the wind on the right column (5 kN/m). The third case Q_3 is the snow laying on the left girder (5 kN/m) and the fourth case Q_4 is the snow laying on the right girder (5 kN/m). There is a defined objective function $F(Q_i, x_0, y_0)$, which is equal to the maximum of the bending moment in the frame.

$$(4.1) \quad F(Q_i, x_0, y_0) = \max(\wedge_{j \in \Omega} M_j)$$

where: $i = 1, \dots, 4$.

The area of a search for the center of rotation is limited by ranges $x \in (-6.1 \text{ m}, 6.1 \text{ m})$ and $y \in (-3.0 \text{ m}, 10.1 \text{ m})$ in each load case. The grid of the point has a spacing of 0.5 m. Based on the calculations done in Dynamo program there were found points. Each of them was assigned a value of the objective function. Discretized, there were also found the values of the bending moment in the node in the ridge – also assigned to the points. The data from both files was visualized using program Autodesk Civil 3D. (Fig. 6a–7d). The visualization shows the values of the moments in the portal frame for different locations of the center of rotation – where blue is the maximum value and red is the minimal value. There are also a green lines and blue lines that represent a path of points with maximal moment in the whole frame that is to be minimized. The lines were found using the least squares method, to show the potential, best location for the center of rotation.

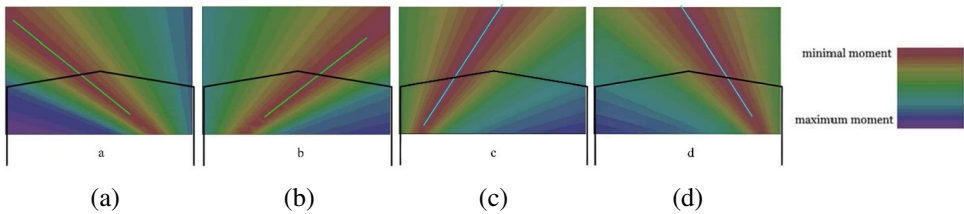


Fig. 6. The graphs of the values of the moments in the portal frame for all four load cases, where: a) Q_1 ; b) Q_2 ; c) Q_3 ; d) Q_4

After finding a line of points that are potential centers of rotation with maximal bending moment, the search area was analyzed based on the $G(Q_i, x_0, y_0)$ function, which value is determined based on a sign of the bending moment. The customized type of the surface style in Autodesk Civil 3D allowed to divide search area into two parts: a green one representing potential centers of rotation with maximal bending moments that have positive sign (+) and red one where maximal bending moments have negative sign (-). In Fig. 7, the search area for this example is divided into those parts for each load case and has lines from Fig. 4 marked. It was observed that for wind loads (Q_1 and Q_2) the found lines have only maximal bending moments with positive sign (green area) (Fig. 5a and 5b) and for snow loads (Q_3 and Q_4) the lines have only maximal bending moment with negative sign (area) (Fig. 7c and 7d).

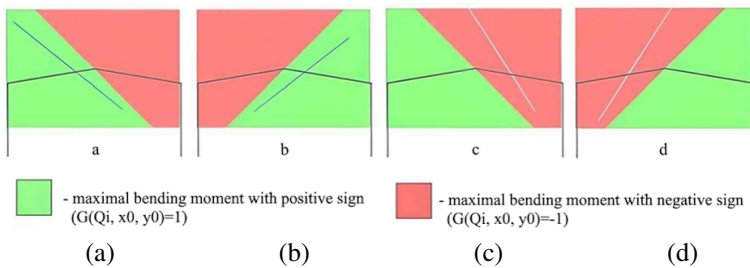


Fig. 7. The lines from Fig. 4 highly visible being in the positive or negative value of $G(Q_i, x_0, y_0)$ function in search area, where: a) Q_1 ; b) Q_2 ; c) Q_3 ; d) Q_4

After layering Fig. 7b over 7a (Fig. 8a) and Fig. 7d over 7c (Fig. 8b), it was noticed that the lines from the first and second load case have an intersection point under the ridge node almost on the symmetry axis of the frame. Analogically, the lines from the third and fourth case have an intersection point over the ridge, also on the symmetry axis of the frame. Thus, there can be assumed two centers of rotation in those points: $O_{1,2}(0.00, 0.30 \text{ m})$ – active when wind loads act on the structure (Fig. 8a) and $O_{3,4}(0.00, 4.52 \text{ m})$ – active when snow loads act on the structure (Fig. 8b).

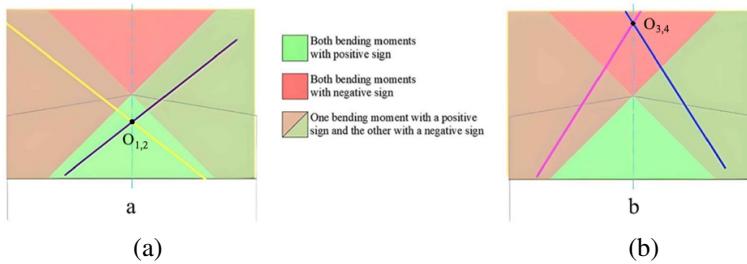


Fig. 8. The yellow (Q_1), purple (Q_2), blue (Q_3), and pink (Q_4) lines showing that the sign of the bending moment in the node is the same, separately for the first two cases and the last two in the intersection points of the lines

Finally, when the new centers of rotation were found (Fig. 9), it was possible to design a proposed version of the node that was presented earlier in section 2.1. in Fig. 3. The axes of bars inside the node intersect exactly in found points.

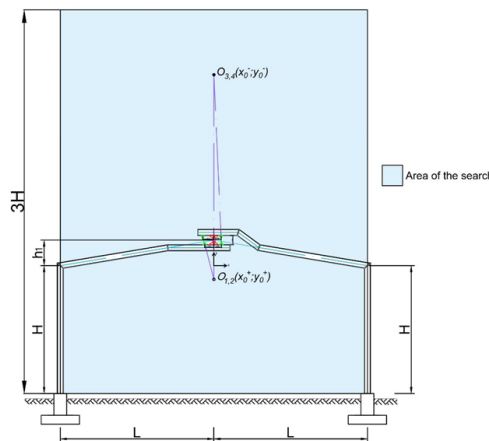


Fig. 9. New centers of rotation found for the first example

The efficiency of the designed connection was checked using Autodesk Robot program. There was created an analytical model of the portal frame with proper mechanical characteristics as for sections from the beginning of this section. Secondly, there were created 4 load cases, the same as in the algorithm (snow and wind load), as well as the self-weight case, all with the value of 5 kN/m.

The output values of the objective function (the maximal bending moment occurring in the frame) are shown in Table 1. The results from a benchmark model – a frame with a classic rigid rigid connection were used as the comparative values.

Table 1. The values of the objective function received from the designed node compared with a classic solution

Objective function – maximal bending moment [kN·m]			
Load scheme	Hinged node	Bioinspired node	Reduction
self-weight	4.58	4.38	4%
snow on the left/right girder (5 kN/m)	38.02	25.44	33%
wind from the left/right (5 kN/m)	39.17	36.88	6%

Analyzing the given values of the objective function, it can be stated that there is indeed a significant reduction of the maximum moment occurring in the frame, not only in case of the loads $Q_1 - Q_4$ – that were crucial while designing the node – but also in other types of engineering loads e.g., the self-weight. The reduction is especially noticeable for snow loads.

Additionally, there were computed maximal values of other internal forces: axial and shear and they were also compared with the benchmark model in Table 2.

Table 2. The values of maximal axial and shear force in a designed model compared with a classic solution

Maximal axial force [kN]			
Load scheme	Hinged node	Bioinspired node	Reduction
self-weight	6.38	6.81	-7%
snow on the left/right girder (5 kN/m)	22.81	21.44	6%
wind from the left/right (5 kN/m)	11.58	12,02	-4%
Maximal shear force [kN]			
Load scheme	Hinged node	Bioinspired node	Reduction
self-weight	1.66	2.09	-26%
snow on the left/right girder (5 kN/m)	21.25	21.18	0%
wind from the left/right (5 kN/m)	19.79	19.2	3%

For these internal forces, the reduction depends on a load case. For axial forces, the reduction is only in snow loads, while for self-weight and wind load there is no reduction – only a slight increase. For shear force, there is a slight reduction for wind load and an increase in self-weight – however, this increase is only about 0.5 kN.

In addition, there were also compared the biggest displacements of nodes for both models. (Fig. 10) For both models, the biggest displacement was for wind load, however, the values are almost the same.

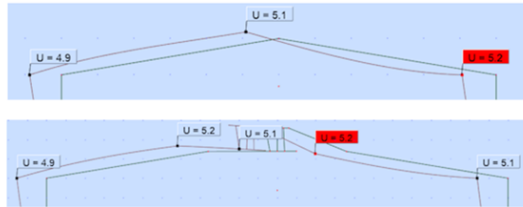


Fig. 10. Nodal displacements for wind load for benchmark model (top) and bioinspired node (bottom)

Finally, all members were verified for ultimate limit states (ULS) in Robot (Fig. 11).

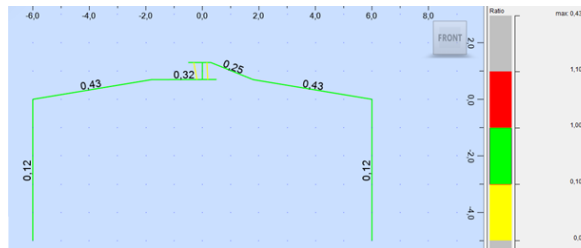


Fig. 11. Member verification for frame with bioinspired node

4.2. The 3D model of a steel hall

The same objective function has been checked for a 3D model of a steel hall. It contains 3 portal frames with the bioinspired nodes (Fig. 12). There was also added the cladding and the combinations of the loads, done accordingly to the Eurocodes [12]. The combinations were made from the self-weight, snow, and wind for the central region in Poland.

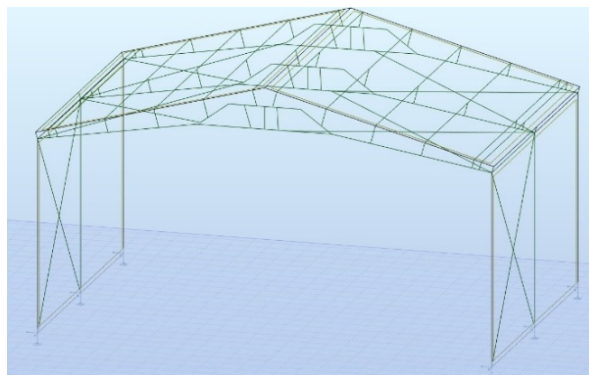


Fig. 12. The steel hall with 3 portal frames with bioinspired nodes imported to Autodesk Robot

Analogically to the 2D model, there were examined the graphs of the bending moments on each bar. (Fig. 13a) The biggest value of the bending moment was compared to the biggest bending moments in a benchmark model (Fig. 13b). It contains 3 portal frames with articulated node in the ridge, has a comparable weight and the same load combinations. The reduction of the biggest bending moments was calculated and is equal to 22,81%.

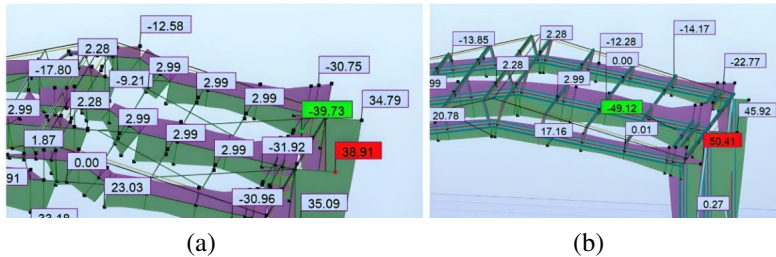


Fig. 13. The maximum bending moments in the designed steel hall (a) and the benchmark model (b)

It was noticed that such significant reduction of the moments and displacements is caused by the effective optimisation of the portal frame by the bioinspired nodes, as well as the specific distribution of the moments due to the truss-like structure.

There were also examined the maximum displacements of the nodes in the steel hall (Fig. 14a) and they were, again, compared to the benchmark model (Fig. 14b). There was a noticeable reduction of the displacements.

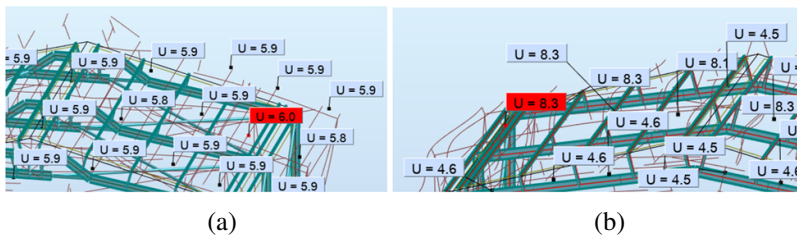


Fig. 14. The biggest displacements in the designed steel hall (a) and the benchmark model (b)

5. The second example of the objective function – the maximum moment in the corner of the frame

5.1. The 2D model of a portal frame

The second example of designing a node was calculated using the frame with 4 meters high columns and girders that spans 7 meters horizontally. It has pinned supports. As for the loads, there are the same four load cases with the same values as in section 4.1. In this example, objective function is different and it is the value of bigger bending moment appearing in the frame's corners (M_{LC} , M_{RC}).

The calculations were also made using Dynamo program and the Autodesk Civil 3D program. The procedure was analogical to the first example. The results showed that the minimal values of the objective function for the first two cases, as well as in the first example, also have an intersection point on the symmetry axis below the node in the ridge. The sign for their bending moments is also the same (Fig. 15).

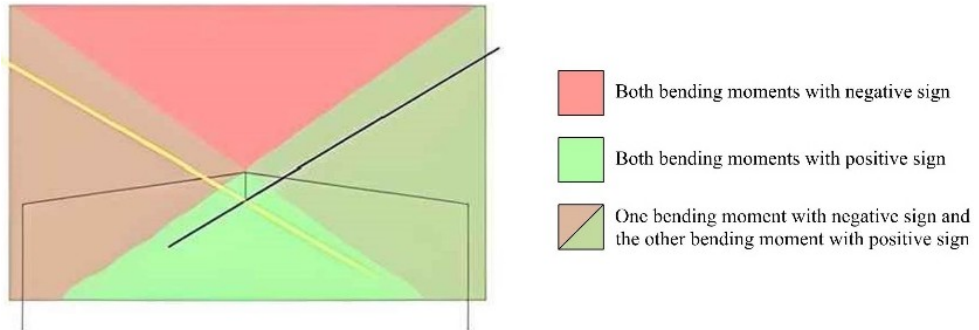


Fig. 15. The intersection point of the lines made of minimal value of the objective function for the first and the second case

However, in the third and the fourth load case, the lines made of minimal values of the objective functions are parallel to each other and are colinear with the columns (Fig. 16).

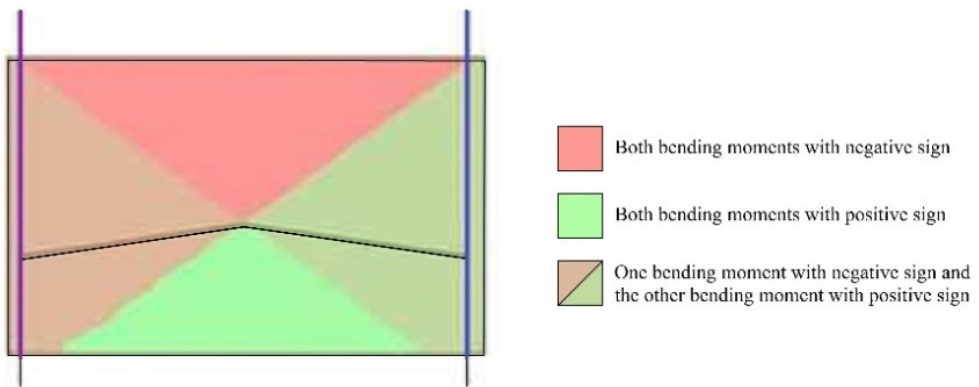


Fig. 16. The parallel lines made of minimal value of the objective function for the third and the fourth load case

Therefore, there is one center of rotation in the intersection point with coordinates (0.00, 0.10 m) – that is active when wind loads act. The second intersection point is in infinity in vertical direction – corresponding to the load scheme from the third and the fourth case. In that case, there has been suggested the design of the node in the ridge as shown in Fig. 17.

The calculations done in Robot program show that the value of the objective function in this case is lowered by 10% and 34% in the case of the frame designed with a bioinspired node

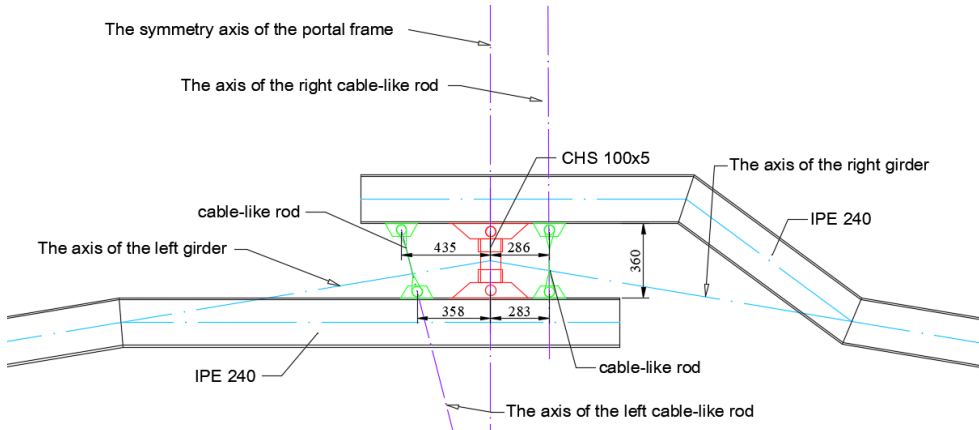


Fig. 17. The design of the node for the second example of the objective function

than for the pinned frame. In the case of the self-weight, which was not included in the design process, there is also the minimalization of the objective function's value according to the comparison example.

6. Summary and conclusions

The analyzed examples allow to state that the proposed method of specialized design of the bioinspired node in the ridge allows to significantly minimize any chosen objective function, based on the moments appearing in the portal frame. It is possible because there is an additional, available structure's parameter, which is a variable location of the center of rotation of the node in the ridge. It is a designed using the algorithm proposed in this paper, which allows to optimize the construction in comparison to the basic scheme.

The reductions of the moments' values are significant. It gives an opportunity for an economic solution. In the next phases of the research, the authors plan to use the proposed design in different frame's nodes or create an alternative design. Among the authors' further work plan, there is also testing of the objective function based on the stresses and the displacement of the frame, but also to make the prototype of the steel hall containing bioinspired nodes, based on the presented solutions.

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The structure of the node in the ridge proposed in this article has been reported on 28.09.2022 to the Patent Office of the Republic of Poland with a number P.442383 as an invention called „Węzeł kalenicowy ramy portalowej” (Eng. “The node in the ridge of the portal frame”). The presentation based on this paper was presented at the 25th International Conference on Computer Methods in Mechanics on 07.09.2023 in Gliwice, Poland, and received

an honorable mention in the Jan Szmelter Award for the young researchers participating in this conference. This work was supported by the Rector of the Lodz University of Technology under the program Excellence in Engineering: Talents in Research with Opportunities Program 2022/2023, 2023/2024, and 2024/2025.

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Użycie inspirowanych bioniką węzłów ze zmiennym środkiem obrotu w celu optymalizacji momentów w ramie portalowej

Słowa kluczowe: konstrukcje stalowe, optymalizacja, rama portalowa, węzły inspirowane bioniką

Streszczenie:

Powyższa praca przedstawia algorytm zaprojektowania i przykłady zastosowań innowacyjnego rozwiązania węzła kalenicowego w ramie portalowej. Inspiracją była mechanika stawu kolanowego, szczególnie zjawisko przesuwu środka obrotu kolana podczas zginania. Klasyczne rozwiązania konstrukcyjne

mają stały środek obrotu w miejscu połączenia, natomiast w nowym węźle jego lokalizacja zmienia się w zależności od obciążenia. Wykorzystując algorytm minimalizacji funkcji celu zawarty w pracy, autorzy przedstawili dwa przykładowe zaprojektowania bionicznego węzła. W pierwszym przykładzie autorzy za funkcję celu obrali wartość momentu zginającego w kalenicy ramy. Najpierw utworzono program w Dynamo, który oblicza moment zginający w węźle kalenicowym dla 4 przypadków obciążenia dla środka obrotu znajdującego się w każdym punkcie wybranego obszaru poszukiwań. Następnie, współrzędne punktów z odpowiadającymi im wartościami momentów i znakami, zostały zaimportowane do Autodesk Civil 3D, gdzie stworzone zostały po dwie mapy dla każdego przypadku obciążenia. Wykorzystując metodę najmniejszych kwadratów utworzono linie przechodzące przez najmniejsze wartości momentów. Autorzy zauważyli, że po dobraniu map w pary i nałożeniu ich na siebie utworzone linie przecinają się na osi symetrii ramy, odpowiednio dla każdej z par. Dla pierwszej pary punkt przecięcia znajdował się na osi symetrii ramy pod węzłem kalenicowym, natomiast dla drugiej też na osi symetrii ramy nad węzłem. Autorzy ustanowili te dwa punkty środkami obrotu dla nowego węzła, które są automatycznie wybierane w zależności od obciążenia. W powyżej pracy zaproponowano wygląd węzła z tymi środkami obrotu. Model w Autodesk Robot wykazał redukcję momentów względem klasycznego sztywnego połączenia. W drugim przykładzie autorzy za funkcję celu wybrali większą z wartości momentów zginających występujących w narożach ramy. Wykonano analogiczny program, wykresy i obliczenia. Po nałożeniu na siebie wykresów, tak jak odbyło się to w pierwszym przykładzie, zauważono, że dla pierwszej pary obciążeń punkt przecięcia linii przechodzącej przez najmniejszą wartość momentu znajduje się pod ramą na osi symetrii. Jednak w przypadku drugiej pary obciążeń linie są do siebie prawie równoległe. Po utworzeniu modelu w programie Autodesk Robot także zauważono redukcję wartości momentów w porównaniu z klasycznym modelem. Podsumowując, powyższe innowacyjne rozwiązanie pozwala na optymalizację ramy portalowej poprzez dobór funkcji celu i minimalizację jej wartości, wykorzystując przedstawiony algorytm.

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