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Structural Performance of Bolted Lateral Connections in Steel Beams under Bending Using the Component-Based Finite Element Method

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Featured Application: The findings of this research can significantly contribute to the design and construction of efficient and safe steel joints for building structures.

Abstract: Structures must provide strength, stability, and stiffness to buildings and at the same time be efficient. This study addressed the effect of design elements and parameters on the strength of bolted lateral connections in steel beams under bending using the component-based finite element method. The variables evaluated were plate thickness, horizontal and vertical spacing between bolts, and geometric arrangement of bolts. Finite element software was used to evaluate the stress state of the junction plate, its plastic deformation, and bolt shear. A sensitivity analysis was performed to determine which bolt arrangements result in safer and more efficient designs using the same components. Stress distribution within the junction plate and plastic deformation values were used to evaluate the structural performance of the joints according to EuroCode 3. The results showed that placing bolts near the edge of a plate affected the bolts' utilization, especially with thinner plates. Additionally, introducing an offset between central and outer bolt rows is not recommended as it worsened the stress distribution and the structural performance.

Keywords: bolted connections; steel structures; finite element method; ultimate limit state

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Citation: Morido-García, G.; De Santos-Berbel, C. Structural Performance of Bolted Lateral Connections in Steel Beams under Bending Using the Component-Based Finite Element Method. *Appl. Sci.* **2024**, *14*, 3900. https://doi.org/10.3390/app14093900

Academic Editor: Roberto Citarella

Received: 29 March 2024
Revised: 21 April 2024
Accepted: 30 April 2024
Published: 2 May 2024

1. Introduction

Structures must provide strength, stability, and stiffness to buildings and at the same time be efficient, ensuring that they can withstand extreme events. Connections are fundamental elements of steel structures because they are responsible for transferring loads between different steel members in the structure. Furthermore, connections are important because they can have a significant impact on the overall cost and construction of the steel structure. The design of the connections must be optimized to minimize the amount of steel used, while ensuring that the connections are strong and reliable. This requires a careful analysis and design to ensure that the connection is the most efficient and economical solution.

The bolted connections are based on classic solutions of the traditional ribbed construction. Particularly, bolted lateral connections attach steel profiles with plates arranged as joint covers. Their use is especially indicated in those cases where the frontal solutions are not usable due to geometrical constraints, or because they do not allow some of the degrees of freedom of movement required for the joint [1]. On the one hand, bolted lateral connections avoid tensile stresses perpendicular to the rolling plane of the plate, an indispensable condition for joining the earlier steels, which were very susceptible to sheet defects. On the other hand, this solution is typically selected for long-span beams that would require special transportation, which would increase its final cost significantly. Therefore, a joint is introduced in the beam that works well under shear forces, although it is true that this type is not as effective against bending moments. Thus, when selecting the joint location, it must be placed at approximately one fifth of the span, where the bending moment envelope is closest to zero. Possible joint failures include breakage of the bolt and breakage of the sheet metal, either by tearing or buckling. Given the location of the joint in the structure, in a section subjected to a certain shear loading and with low bending moment loading, failure of the steel profile would occur in the web.

Moreover, circumstances may arise on construction sites that may constrain the availability of materials or represent an opportunity to reduce costs, e.g., in relation to the length of the steel profiles, thicknesses of the cover plate, etc. If changes are made to the original design, they must be code-compliant and ensure safety.

2. Background

Limit states are those situations for which, if exceeded, the building may be considered as not meeting any of the structural requirements for which it was designed. In the case of the ultimate limit states, they are those that in the case of being exceeded, constitute a risk for people, because they produce the rupture of some structural elements, and with it the total or partial collapse of the building [2].

The finite element method (FEM) is a widespread numerical method for solving structural analysis models, dividing the system into smaller, simpler elements, and modeling each element with equations that describe its mechanical behavior. The calibration process involves comparing the output of the simulation with experimental data obtained from physical testing, and adjusting the model parameters until a satisfactory match is achieved. Current software suites provide calibrated FEM models that reproduce structural performance of steel connections as well as the interaction between elements in a realistic manner [3,4].

Research has recently been conducted on evaluating the performance of bolted connection steel plates applying the FEM and the discontinuity layout optimization (DLO) [5]. The interactions between all the structural parts involved in a bolted connection are easier to model when using the FEM. In addition, the FEM provides information on displacements and stresses distribution prior to collapse. In turn, two commonly used possibilities to analyze the structural behavior of steel joints are solid and shell FEMs. For example, solid FEMs require more computational effort while providing more accurate modeling of bending moment resistance in steel joints [6]. Thanks to the use of the FEM, it is possible to optimize structural design as well as to develop reliable structural solutions for frames and connections between members [7]. Different types of joints have been tested, particularly T-joints and plate connections have been extensively studied using FEMs [3,4,8]. Shell elements have been used to simulate laminates in 2D FEM single-lap joints, improving the simulation of the stiffness of bolts and laminates as well as the model's ability to simulate the secondary bending [9].

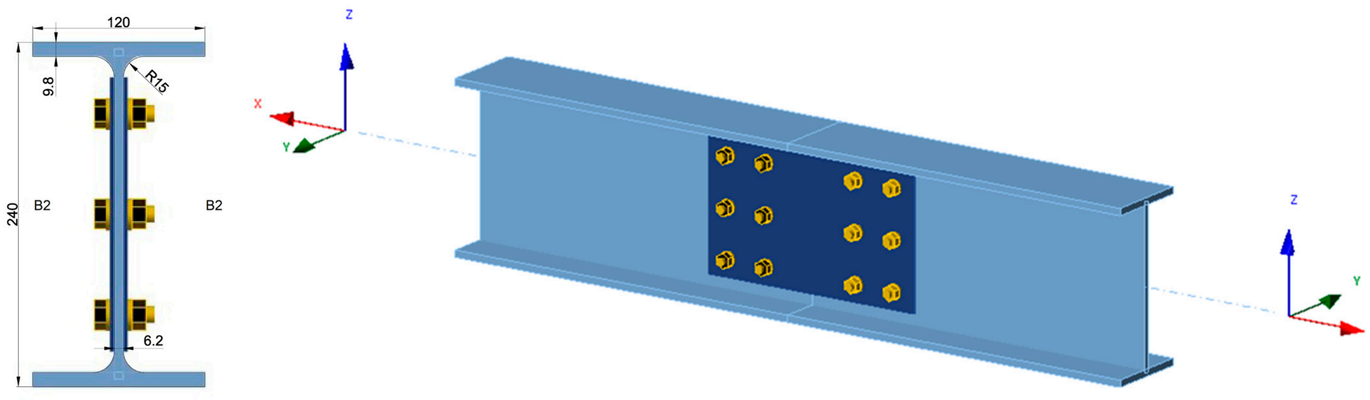
The FEM provides valuable information about the interaction between the elements that make up the joint. A literature review shows that traditional design methods, which assume a rectangular stress block in plates, may inaccurately represent stress distribution under base plates, especially with thicker plates, leading to potentially non-conservative designs [10]. An adequate arrangement of the bolts improves stress distribution in connection plates [11]. Thin plates can benefit from the clamping force generated during the rivet installation process, which creates a localized compressive stress that helps to prevent the initiation and propagation of cracks. However, this positive effect diminishes as the thickness of the material increases [12].

Modeling of composite bolted joints recently incorporated friction, bolt-hole clearance, bearing damage, and joint failure [13]. Composite bolted joints can be modeled through a collection of components replicating the elastic properties of the bolt as demonstrated by Belardi et al. [14]. A beam model simulated the structural behavior of the bolt shaft while a nonlinear spring was employed to represent the frictional force between the plates, accounting for bolt-hole clearance, allowing the calculation of the displacement caused by the contact between the bolt shaft and the plate holes. The deformation of the plate holes was modeled by considering a beam resting on an elastic foundation. Additionally, a second spring component was utilized to account for the rotational stiffness linking the bolt head and shaft, as well as the elastic support provided by the plates to the bolt head.

The regulatory framework for steel connections in Europe is defined by a structural standard for steel and composite connections, known as Eurocodes, prescriptions that have been met for the definition of the case studies developed in this study.

3. Materials and Methods

The joint case proposed in this study connects two IPE240 identical profiles of S275 steel by means of two plates on both sides of the web and twelve bolts (Figure 1). The plate dimensions are conditioned by the geometry of the IPE240 profile. As shown in Figure 1a, the meeting of the flange and the web in the profile includes a circular root, so that the available web height to accommodate the plate is 190 mm. To mount the bolts inside the plate spaced at similar distances horizontally and vertically, a length of 320 mm is selected. Furthermore, these dimensions allow us to modify the position and arrangement of the bolts, whose effect is to be studied. In addition, the parameters associated with strength, dimensions, and bolt tightening are factors that are maintained for all case studies. Particularly, prestressed connecting elements included high-strength bolts. According to the standard EN ISO 4014/4022 [15], which specifies the characteristics of hexagon head bolts, an M12 C8.8 bolt was selected. Its yield strength is 640 N/mm^2 and its tensile strength is 800 N/mm^2. As contact surfaces do not need to be prepared in a special manner, the joint studied is grade A.



(**a**) (**b**)

Figure 1. Joint components: (**a**) Cross-section view with dimensions in mm; (**b**) axonometric view.

The failure modes of this connection include tearing resistance for bolt groups, local bending, crushing, and block tearing.

IDEA StatiCa v.20 software was used to compute the resistance and the stress state of the joint elements. The program works with the component-based finite element method (CBFEM), which is the combination of two methods: the FEM and the component method (CM) [16]. The CM is implemented in the current Eurocodes [17–19] and applied in the majority of software for structural steel used in Europe. The component model of connections begins and stems from the decomposition of a joint to components. The constitutive equations of the material model the deformation behavior in relation to the normal and shear forces. The connection components are grouped to examine joint moment–rotational behavior and classification representation in a spring-shear model. Interactions between components incorporate boundary conditions to simulate the influence between the behavior of the connection elements for their consideration in the aggregate analysis of the connection structural performance [20]. The IDEA StatiCa software calculation procedure is supported by an extensive experimental validation campaign [16].

The CM is based on standard procedures that evaluate the internal forces in the geometric layout of the connection and their verification, involving the prediction of resistance, stiffness, and deformation capacity. It permits predicting the 3D performance of steel joints under arbitrary loading despite the complex phenomena (nonlinearities, residual stresses, geometrical configurations, etc.) affecting the behavior of structural steel [21]. The weakness of the standard CM lies in the analysis of internal forces and stress in a joint.

To overcome this limitation, the CBFEM method replaces the specific analysis of the internal forces in the joint with the general FEM. Check that methods of specific components like bolts, which are modeled as nonlinear springs, are performed according to the standard CM (Eurocode). In turn, special FEM components permit modeling the bolts behavior in a joint. All parts of one-dimensional members and all additional plates are modelled as plates. As elements are made of steel and their mechanical behavior is significantly nonlinear, the real stress–strain diagram of steel is replaced by the ideal plastic material for design purposes in building practice. The advantage of ideal plastic material is that only the yield strength and modulus of elasticity must be known to describe the material curve. As these elements are considered as an ideal elastic plastic material, their internal forces can be retrieved for evaluation. Although the granted ductility of construction steel is 15%, the real usable value of limit plastic strain is 5% for an ordinary design [22]. The stress in steel cannot exceed the yield strength when using the ideal elastic–plastic stress–strain diagram.

The CBFEM method aims to model the real state precisely. Meshes of plates from different components are not merged, and no intersections are generated between them. Instead, a mesh of finite elements is generated on each individual plate independently on mesh of other plates. Between the meshes, special massless force interpolation constraints are added. They ensure the connection between the edge of one plate and the surface or edge of the other plate. End forces on members are applied as loads on segment ends, with internal forces from theoretical nodes transferred to segment ends, maintaining force values while adjusting moments due to force actions on corresponding arms, without connecting inner ends of segments [16]. The model incorporates shear stress transmission by crushing and tensile–shear interaction. This unique calculation model provides excellent results, both from the point of view of precision and a speed analysis. Figure 2 illustrates the joint model as displayed by IDEA StatiCa.

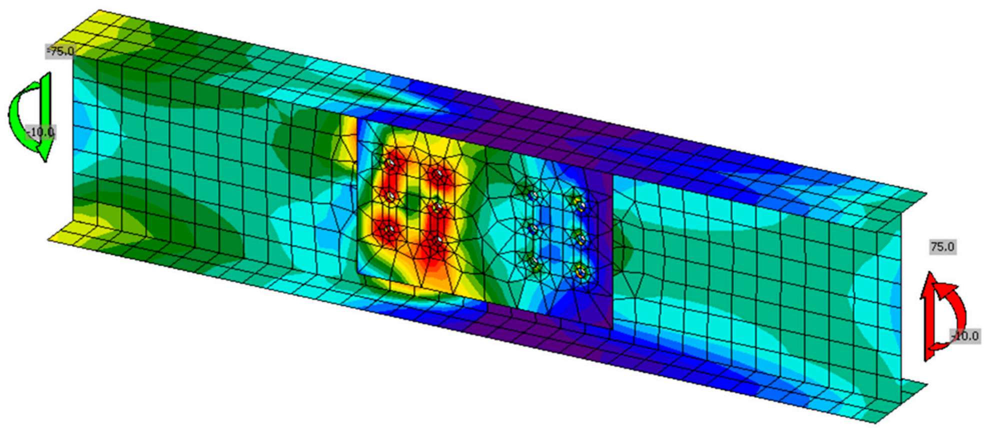


Figure 2. Joint model in IDEA StatiCa using finite elements with the range of colors representing the state of internal tensions.

Circular holes are arranged both in the IPE240 profile and in the plates. As stipulated by Eurocode 3 Part 1–8 [17] for M12 and M14 bolts, the standard diameter of the holes equals the diameter of the screw shank plus 1 mm (Figure 3). Spacing between bolts and between bolts and the plate border is regulated by Eurocode 3 Part 1–8.

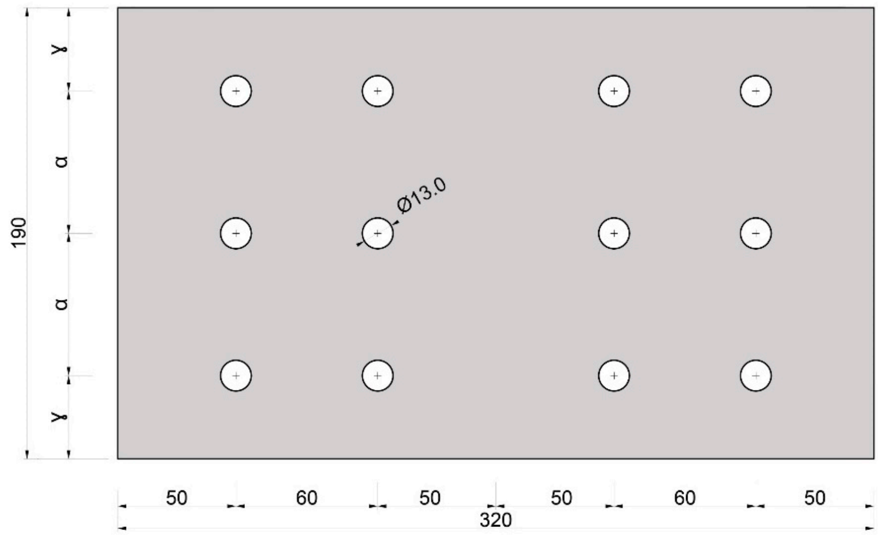


Figure 3. Dimensions of steel plate and position of holes.

The case studies assume a small bending moment value in relation to the shear stress. This fact determines the placement of joint covers only in the web zone of the structural section. A total of 80 case studies were analyzed with the same static loading hypothesis, including the weighting coefficients of actions, resulting in a bending moment stress of 10 kN-m and a shear stress of 75 kN. These values constitute the boundary conditions, with no additional constraints considered. As a result, the model is in equilibrium after computation if the internal forces are added at the ends of related members.

Table 1 contains model and mesh CBFEM parameters as well as calculation parameters as introduced in IDEA StatiCa settings. A multiple of the height of the section is used to determine the default length of a standard element. The ratio of the plate edge length to the number of edge elements determines the number of elements in the largest flange or web. Each calculation was conducted with 25 iterations with up to three divergence steps for its evaluation. The finite element mesh is composed of linear elements. To select the size of the finite elements, a pilot sensitivity analysis was conducted. Element sizes of 2 to 8 mm, 5 to 20 mm, and 10 to 40 mm were set to analyze the effect of the mesh size on the target parameters of this study. It was concluded that reducing the mesh size beyond the latter values did not provide significant additional precision while the computational time was greatly increased. As a result, the maximum element size was set at 40 mm and the minimum element size was set at 10 mm since it provided a sufficient fineness to obtain precise enough results without delaying the computational calculation, while the mesh layout provided sufficient adaptation to the shape of the connection components.

Table 1. Model and mesh CBFEM parameters.

Parameter	Value
Default length of standard element	1.5
Minimum element size	10 mm
Maximum element size	40 mm
Number of elements in flange or web	8
Number of iterations in analysis	25
Diverging iteration count	3

The results of joint designs have been further checked and validated using the spreadsheets for lateral bolted joints prepared by Ortiz et al. [1] These are based on the abovementioned EuroCode 3 specifications.

4. Results and Discussion

In this section, the results of the analysis of case studies are described. First, the effect of modifying the vertical spacing between bolt rows was evaluated. Second, the effect of the horizontal spacing between the vertical edge and bolts was assessed.

4.1. Vertical Spacing between Bolt Rows

The first set of case studies considered a steel plate where five hypotheses concerning the vertical spacing between bolt rows are contemplated: 40, 50, 60, 70, and 80 mm. Four steel plate thickness values were combined with each of them: 3, 3.5, 4, and 5 mm. It must be noted that the selected spacing distances comply with the minimum distance to plate edges according to Eurocode 3 [17]. These variations were studied while the horizontal spacing between bolts was kept constant. Figure 3 represents the dimensions and geometrical arrangement of the bolt holes in the plate.

Equivalent maximum plastic deformation is displayed for the set of case studies in Figure 4. Eurocode 3 [17] requires that this measure does not exceed 5%. Of the 20 cases proposed, 15 complied with the maximum plastic deformation. It can be noted that the 3 mm thick plate complied with the maximum plastic deformation for vertical spacing distances over 60 mm only.

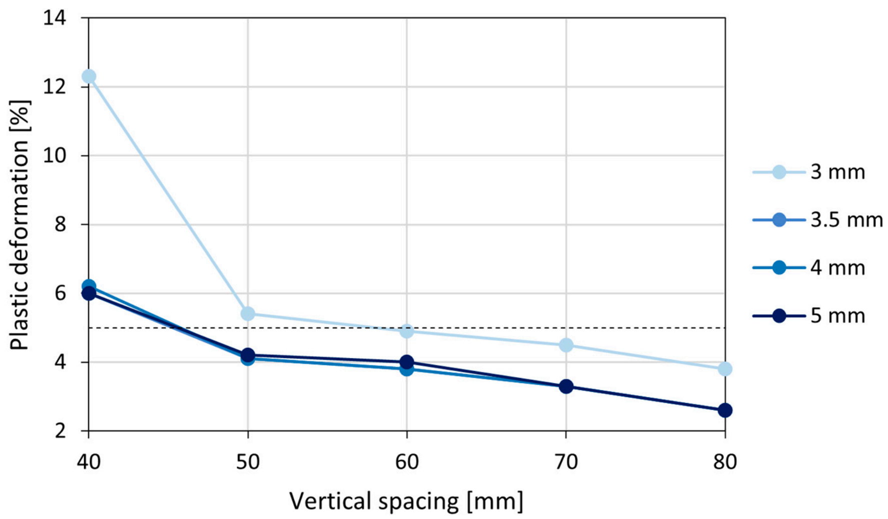


Figure 4. Equivalent plastic maximum deformation for horizontal spacing of 50–60 mm.

Figure 5 displays the contour plot of plastic deformation in the joint with the 3 mm thick plate and 70 mm vertical spacing along with the color scale legend. Plastic deformations are located in the contact zone between the bolt and the profile or the metal plate. In the profile web, it can be noticed how the kinematic field of plastic deformations responds to a rotational field with the center at bolt #13. A similar situation is observed in the field of plastic deformations connected to the right component around bolt #20.

Figure 6 shows, on the one hand, the von Mises stress map of a 3 mm thick plate with 70 mm vertical spacing between bolt rows. This is one of the cases of the previous set that narrowly met the EuroCode specifications. A significant portion of the plate area reached the yield stress of the steel, which is displayed in dark red. On the other hand, the 5 mm thick plate with 80 mm spacing is the case that met specifications the most loosely. In both cases, it was observed that the most stressed areas are those close to the holes vertically outside and horizontally inside (21 and 23).

The stress state of IPE profiles of the 3 mm thick plate and vertical spacing of 70 mm, one of the designs that met the criteria of EuroCode 3 in an adjusted form, is displayed in Figure 7. It can be observed that the plastic deformation values showed by the color scheme are consistent with the plastic deformations in Figure 5. The von Mises stress distribution showed that the joint plates (Figure 6a) have higher load stresses as the dark red areas are greater in the plates than in the profile web.

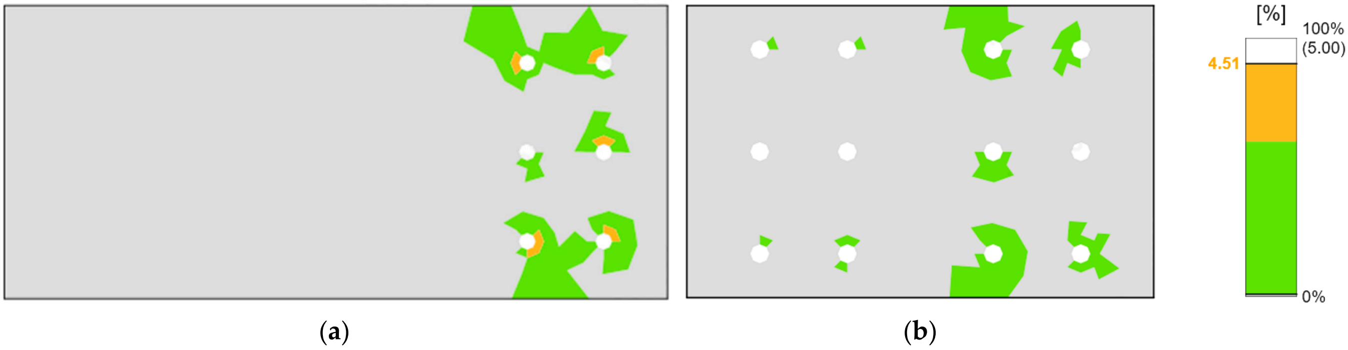


Figure 5. Verification of plastic deformation in joint with 3 mm thick plate with vertical spacing of 70 mm: (**a**) IPE240 web; (**b**) plate.

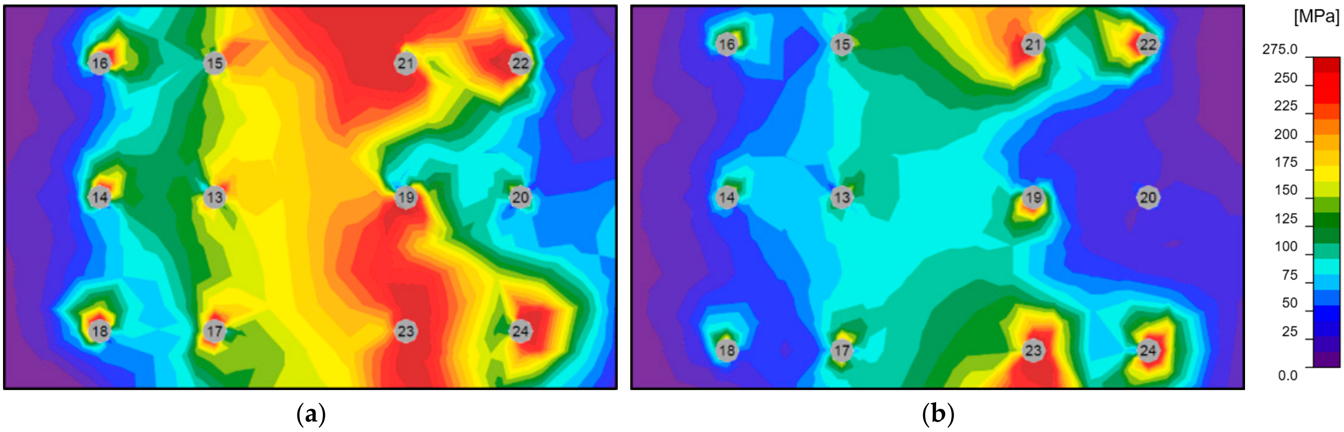


Figure 6. von Mises stress distribution in plates with color scale: (**a**) 3 mm thick plate and vertical spacing of 70 mm; (**b**) 5 mm thick plate and vertical spacing of 80 mm. The numbering of bolts is indicated.

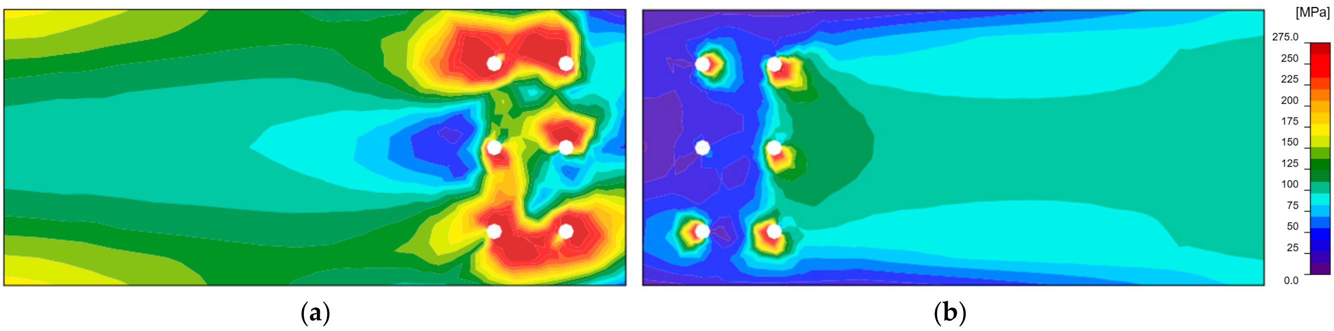


Figure 7. von Mises stress distribution in the web of IPE240 profiles with color scale: (**a**) left end; (**b**) right end.

Regarding the calculation of bolt shear utilization, it can be observed in Figure 8 that 15 of the 20 cases proposed met the maximum plastic deformation. The case studies with smaller vertical spacing resulted in a peak shear utilization well above the limit (100%), regardless of the plate thickness. On the other hand, the plate thickness did affect the cases with greater vertical spacing. The greater the thickness, the lower the percentage of shear utilization in the bolts. In intermediate values of vertical spacing, the percentages were all stabilized below the limit and are practically the same in each position. There are

13 possible cases out of 20 that met the specifications. The most efficient connections consisted of a 3 mm thick plate with 60 or 70 mm vertical spacing.

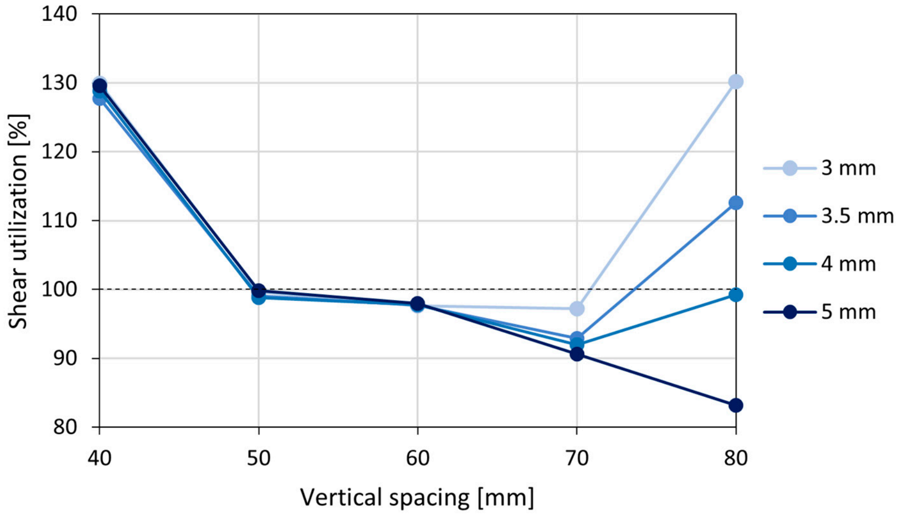


Figure 8. Bolt shear utilization for horizontal spacing of 50–60 mm.

4.2. Horizontal Spacing between Vertical Edge and Bolts

The second set of case studies considers a steel plate where three hypotheses concerning the horizontal spacing between the plate vertical edge and the outermost bolt columns were contemplated, 30, 40, 50, and 60 mm, keeping at 60 mm the bolt columns that are attached to the IPE profile on the same side of the connection. The two vertical spacing values between bolt rows that were found to have better mechanical behavior in the previous section (60 and 70 mm) were considered, and each of them was also combined with four steel plate thickness values: 3, 3.5, 4, and 5 mm. In these cases, the selected spacing distances also complied with the minimum distance to plate edges according to Eurocode 3 [17]. These variations were studied while the vertical spacing between bolts was kept constant. Figure 9 represents the dimensions and geometrical arrangement of the bolt holes in the plate.

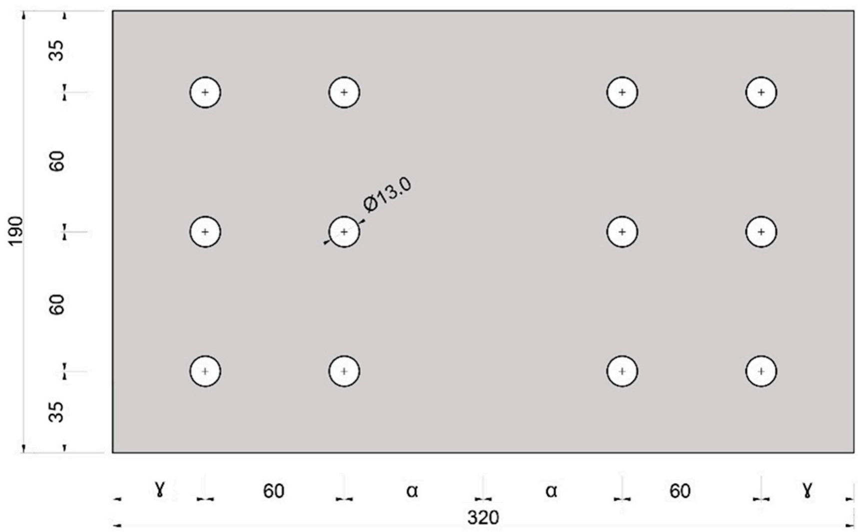


Figure 9. Dimensions of steel plate and position of holes with varying horizontal spacing.

Equivalent maximum plastic deformation values for 32 different designs are displayed in Figure 10. As mentioned above, two vertical offset values between bolt rows were considered: (a) 60 mm, and (b) 70 mm. It is observed that the latter designs showed better mechanical performance not only in terms of bolt shear utilization but also in plastic deformation. In total, 14 of the 16 designs shown in Figure 10a met the maximum plastic deformation of the codes, while 15 of the 16 cases shown in Figure 10b comply with the specifications. Not all cases of connections using 3 mm joint covers complied with the maximum plastic deformation, particularly those where the distance to the vertical edges is less than 40 mm, in contrast to all other plate thickness values. The relationship between the distance to the vertical edge and the plastic deformation was found to be inversely proportional up to 60 mm and virtually linear. As the outer column was moved away from the vertical edge, while maintaining the distance between bolt columns, the strength issues were transferred to the IPE profile. However, the critical resistance values were not reached beyond 60 mm spacing between the vertical edge and bolts since the web thickness is 6.2 mm. It is also observed that, for 60 mm of vertical spacing between bolt rows, at higher plate thicknesses, the effect of increasing the distance to the vertical edges was very small.

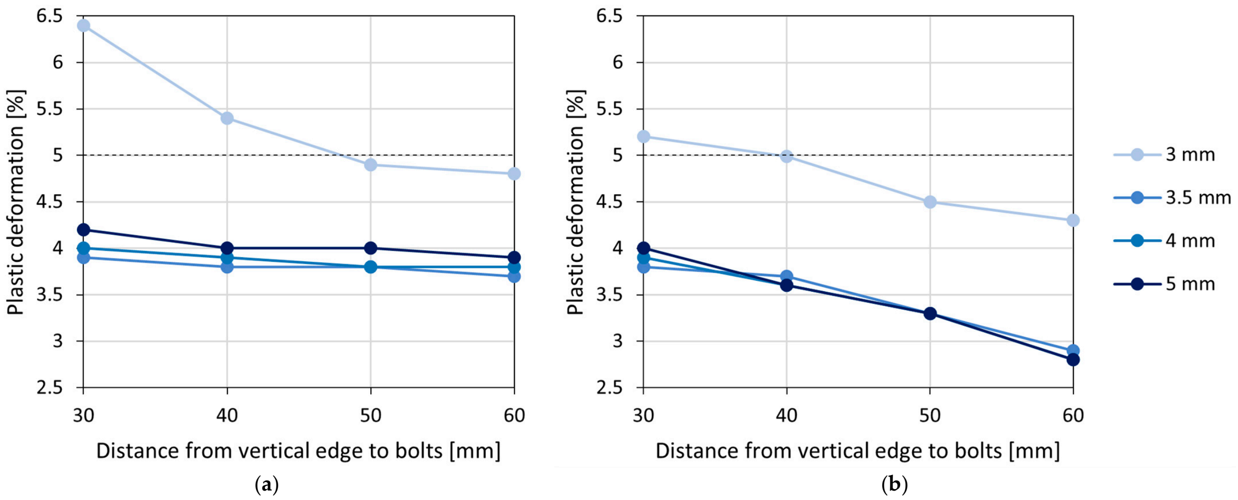


Figure 10. Plastic deformation: (**a**) 60 mm vertical spacing; (**b**) 70 mm vertical spacing.

Figure 11 displays the von Mises stresses in the 3 mm thick plate with 30 mm and 60 mm horizontal spacing to the vertical edge. In both cases, a significant portion of the plate area is displayed in dark red, which indicates that the yield stress of the steel was reached. However, only the first case does not meet the EuroCode specifications due to an excessive plastic deformation. The second case is the design that meets the EuroCode specifications more strictly and can therefore be considered as the most efficient one.

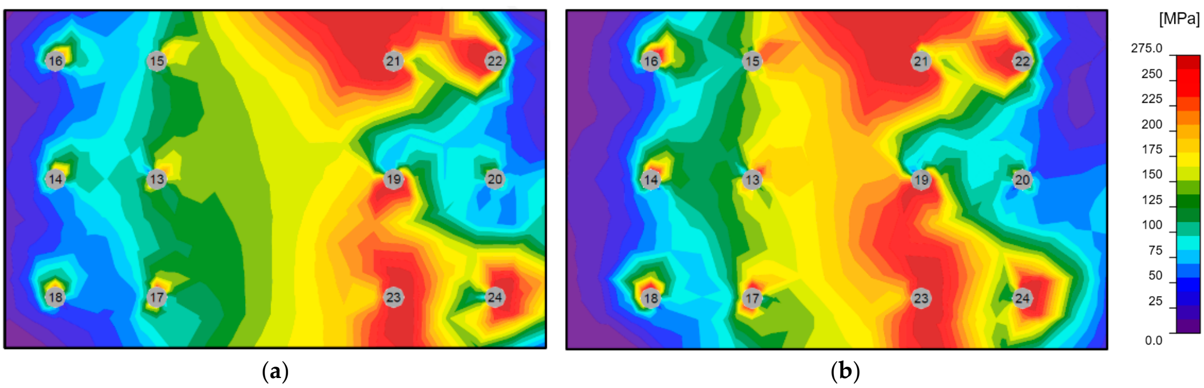


Figure 11. von Mises stress distribution in plates with color scale: (**a**) 3 mm thick plate with 30 mm horizontal spacing to the vertical edge; (**b**) 3 mm thick plate with 50 mm horizontal spacing to the vertical edge. The numbering of bolts is indicated.

4.3. Offset in Central Row

In the third set of case studies, the bolts of the central row were arranged with a 20 mm offset to the lateral ends with respect to the outer ones as shown in Figure 12. This layout can be used for two purposes. The first purpose is to optimize the stress distribution between the joint components. Second, if the joint is to be left as visible, an offset can be introduced for aesthetical purposes. The horizontal spacing between bolt rows on the same side of the joint is kept constant at 60 mm. Concerning the variations considered, values of 40, 50, 60, 70, and 80 mm were assigned to the vertical distance between the non-central row and the horizontal symmetry axis. Second, the plate thickness values considered were, as in previous analyses, 3, 3.5, 4, and 5 mm.

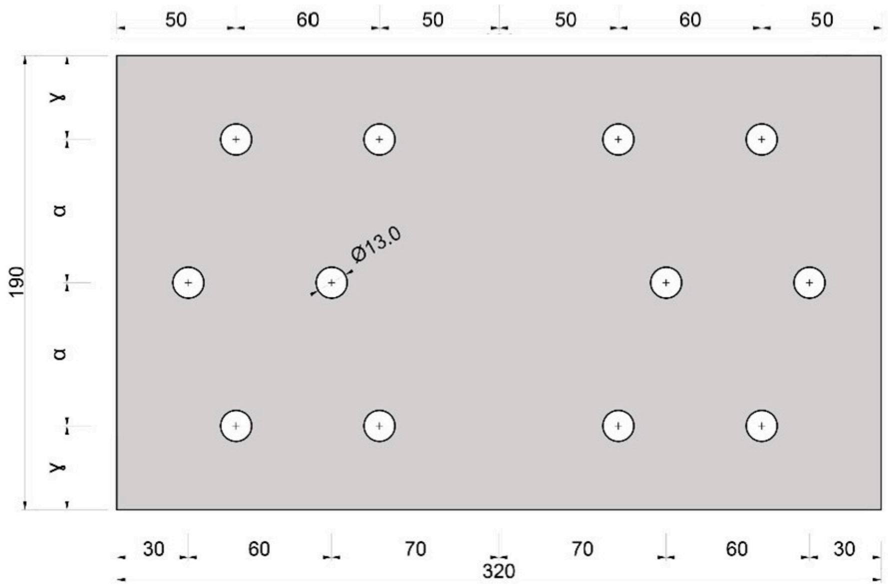


Figure 12. Dimensions of steel plate and position of holes with offset in central row.

As shown in Figure 13, the equivalent plastic deformation decreased as the distance between the horizontal row bolts increased. Out of the twenty cases analyzed, only ten met the maximum equivalent plastic deformation of 5% of the EuroCode. For plate thicknesses equal to or greater than 3.5 mm, the effect of increasing plate thickness was negligible. With an offset in the central row, the distance between horizontal rows must exceed 60 mm to meet the maximum equivalent plastic deformation.

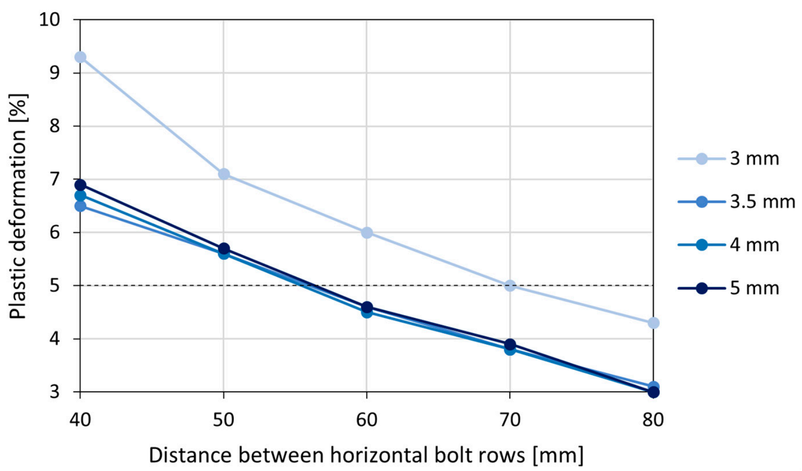


Figure 13. Equivalent plastic maximum deformation for horizontal spacings of 50–60 mm with offset in central row.

Figure 14 shows bolt shear utilization for the different distances between the horizontal bolt rows considered. For spacing between horizontal bolt rows equal to or smaller than 60 mm, the shear utilization decreased with increasing row spacing, virtually independent of plate thickness. If a spacing between rows greater than 70 mm was arranged, shear utilization rose, and the more thin the plate was. As a result, only seven of these joint designs met both EuroCode specifications. By separating the bolt rows by up to 80 mm, the stress distribution between the bolts in the joint is altered, causing the shear stress of the most peripheral ones to increase above their nominal strength when the plate thickness is equal or less than 4 mm.

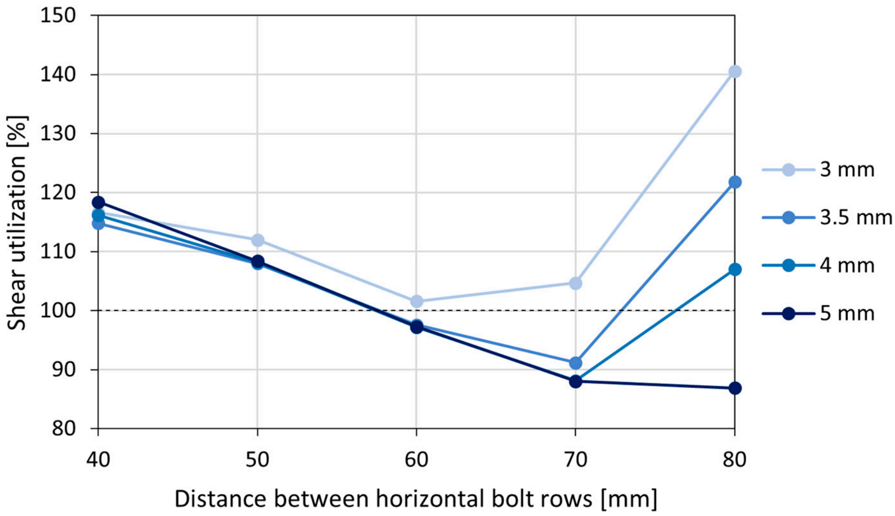


Figure 14. Bolt shear utilization for horizontal spacings of 50–60 mm with offset in central row.

Figure 15 illustrates the von Mises stresses in the 3.5 mm thick plate with 60 mm vertical spacing between row bolts and the 5 mm thick plate with 80 mm vertical spacing between row bolts. The former represents the joint design with the thinnest plate that meets the EuroCode 3 specifications for the defined load stresses. The latter corresponds to the joint design that most satisfactorily meets the requirements. For both designs, we observed the zone with stresses of 275 MPa around bolts 21 and 23, with significant differences in the extension of the zones with high stresses.

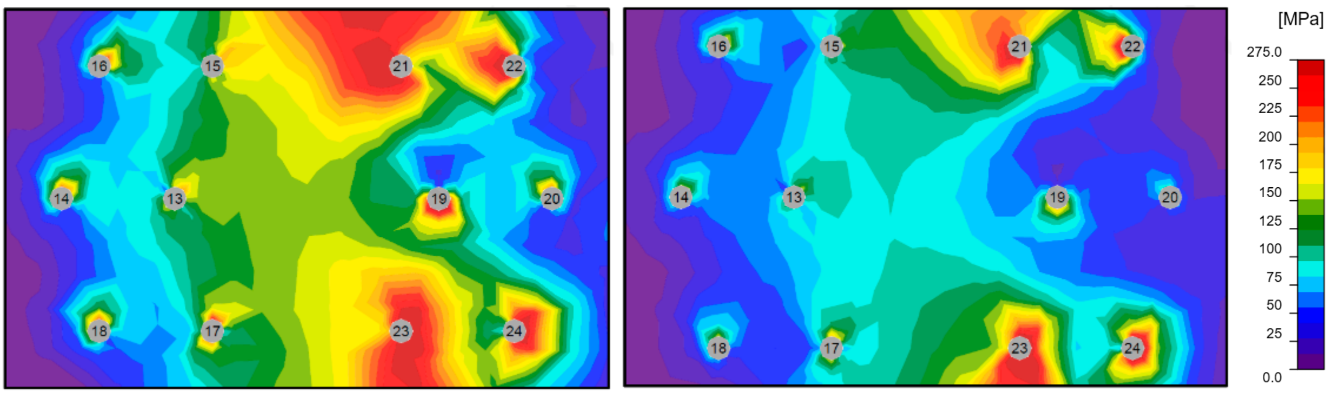


Figure 15. von Mises stress distribution in plates: (**a**) 3.5 mm thick plate with 60 mm vertical spacing between row bolts; (**b**) 5 mm thick plate with 80 mm vertical spacing between row bolts. The numbering of bolts is indicated.

Finally, the results obtained in this last set analyzed were compared with those of the set in which the distribution of the bolts was aligned both horizontally and vertically.

It was observed that the latter designs rendered slightly better structural performances. When thinner plates are used, both the equivalent plastic maximum deformation and the shear utilization of the bolts increase significantly in the cases with an offset in the central row. Among the remainder of the plate thickness values, both the equivalent maximum plastic deformation and the shear utilization of the bolts increase slightly in the cases with an offset in the central row.

5. Conclusions

As fundamental parts of steel structures, connections are responsible for transferring loads between different steel components and have a considerable impact on the overall cost and construction of the steel structure.

This study highlighted the possibility of optimizing steel connection components within the requirements of codes under the restriction of available materials or designs. Different combinations of plate thickness, bolt spacing, and geometric arrangements were tested to observe their effects. The CB FEM was employed to assess the stress state of the junction plate, plastic deformation, and bolt shear. This is a powerful and precise numerical method used to simulate the behavior of structures under various conditions.

The nonlinear behavior of the elements that make up the connection is evident from the results. First, the evaluation of the stress distribution within the junction plate helped in identifying areas of high stress, which varied with the joint design layout with no predictable pattern other than by the finite element analysis. Second, the plastic deformation values showed that the connection components deform plastically under the applied loads increasing more than proportionally for extreme values of the design parameters. Similarly, the examination of the shear forces experienced by the bolts in the lateral connections encountered a disproportionate rise for design parameters at the extreme values.

The results showed that placing the bolts close to the edge of the plate affects the bolts more than the stress distribution of the plate itself when plate thicknesses are in the lower end of the range. In addition, it is not advisable to introduce an offset between the central bolt row and the outer ones since it worsens the stress distribution and the structural behavior of the components. In summary, this text highlights the intricate nature of connection behavior in structural systems, emphasizing the need for comprehensive analyses, careful design consideration, and ongoing optimization efforts to ensure the reliability and efficiency of engineered structures within the constraints of available materials. These effects should be borne in mind by practitioners to optimize the joint design. The findings of this research can significantly contribute to the design and construction of efficient and safe steel bolted joints for building structures.

Author Contributions: Conceptualization, G.M.-G. and C.D.S.-B.; methodology, C.D.S.-B.; software, G.M.-G.; validation, G.M.-G.; formal analysis, G.M.-G. and C.D.S.-B.; investigation, G.M.-G. and C.D.S.-B.; resources, G.M.-G. and C.D.S.-B.; data curation, G.M.-G.; writing—original draft preparation, C.D.S.-B.; writing—review and editing, G.M.-G. and C.D.S.-B.; visualization, G.M.-G. and C.D.S.-B.; supervision, C.D.S.-B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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