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MAIN PARAMETERS OF A BUTT JOINT WITH MEANDER OUTLINE FOR BOX-SECTION COLUMN IN FRAME MOMENT CONNECTION FOR SEISMIC APPLICATIONS

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Abstract: The article presents the research results of the main parameters of a new technical solution aimed at increasing the reliability of an earthquake-resistant frame moment connection between a box-section column and an I-beam beam. This effect is achieved by reducing the number of welds within the connection and performing them under factory conditions. The essence of the solution lies in creating a butt joint of box-section profiles with an outline like a continuous broken line (meander outline) and clamping it from four sides with splice plates using through-bolt high-strength pretensioned bolts. This approach allows welding internal diaphragm plates inside the profile cavity under factory conditions and arranging a frame moment connection with an I-beam beam at the joint location, which can be executed as a bolted unstiffened end-plate connection (BUEEP) or a double-tee moment connection. Previously, an idealized concept of this connection within a steel moment frame was analyzed through numerical modeling under seismic impact, concluding that the performance of the butt joint is equivalent to that of a solid profile. A sensitivity analysis of the stress-strain state of the frame moment connection with a BUEEP was conducted regarding variations in the main parameters of the butt joint with the outline like a meander. These parameters include the meander height, meander fillet radius, thicknesses of flanges and diaphragm plates, as well as the number of bolts per row, their position, diameter, and pretension force value. Based on the data obtained, the parameters exerting the greatest influence on the connection performance were identified, and recommendations for its optimal design were formulated.

Keywords: butt joint, steel frame moment connection, box-section column, seismic, low temperature, weld, ANSYS

ОСНОВНЫЕ ПАРАМЕТРЫ СТЫКА С ОЧЕРТАНИЕМ МЕАНДРА КОРОБЧАТОЙ КОЛОННЫ ДЛЯ СЕЙСМОСТОЙКОГО РАМНОГО УЗЛА

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Аннотация: В статье представлены результаты исследования основных параметров нового технического решения, направленного на повышение надежности рамного сейсмостойкого узла колонны коробчатого сечения с ригелем из двутавра. Эффект достигается за счёт уменьшения в узле количества сварных швов и выполнения их в заводских условиях. Суть решения заключается в создании стыка профилей коробчатого сечения с очертанием в виде непрерывной ломаной линии (очертанием меандра) и обжатии его с четырёх сторон соединительными пластинами с помощью сквозных высокопрочных болтов с предварительным натяжением. Данный подход позволяет приварить в полости профиля в заводских условиях внутренние поперечные рёбра жёсткости и устроить в месте стыка рамный узел с ригелем из двутавра, который может быть выполнен как классическим фланцевым соединением, так и соединением из двух тавров. Ранее идеализированная концепция данного узла в составе полного рамного каркаса была проанализирована численным моделированием на сейсмическое воздействие с заключением, что работа стыка эквивалентна

работе цельного профиля. Проведён анализ чувствительности напряжённо-деформированного состояния рамного узла с классическим фланцевым соединением к изменению основных параметров стыка с очертанием меандра, среди которых: высота меандра, радиус скругления меандра, толщины фланцев и поперечных рёбер жёсткости, а также количество болтов в ряду, их положение, диаметр и величина предварительного натяжения. На основе полученных данных определены параметры, оказывающие наибольшее влияние на работу узла, и сформулированы рекомендации по его оптимальному конструированию.

Ключевые слова: стыковое соединение, стальной рамный узел, коробчатое сечение, сейсмика, низкие температуры, сварной шов, ANSYS

INTRODUCTION

Ensuring structural safety in seismically active regions remains a critical challenge in the design of buildings and structures. An effective approach involves dissipating seismic energy through the plastic properties of materials and the application of seismic isolation systems and vibration dampers, including the utilization of the "soft-story" effect [1–3]. Implementing this effect enhances the dynamic performance of a building or creates a dynamic vibration absorber without requiring specialized devices; however, it necessitates the use of a steel moment frame. Steel is the most suitable material due to its high strength and capacity to sustain long-term performance under plastic deformation. For columns, square box-sections are preferred, as they provide equal strength in both orthogonal directions, exhibit a higher resistance to buckling past the elastic limit, and offer exceptional torsional stiffness [4–6]. According to the Russian Construction Code SP 14.13330.2018 (including Amendments 2–4), the use of box-section columns in steel moment frames is mandatory.

The primary structural and technological challenge lies in the high-quality installation and welding of internal diaphragm plates (diaphragms) inside the cavity of box-section profiles. Current domestic and international concepts of frame moment connections joining an I-beam beam to a box-section column can be categorized into several main types. The first type involves fabricating fully welded columns from individual plates with the preliminary installation of diaphragms [7–11]. The second type moves the diaphragms outside the internal cavity of the column [12–15]. The third type utilizes through-plates that completely interrupt the column continuity, or involves flanged joints arranged at the beam flange levels [6, 16–17]. Finally, the fourth type relies on the use of special cast components [5, 18–21]. It is worth noting that most well-known technical solutions involve a significant number of welded connections. This seriously reduces the overall reliability of frame moment connections under dynamic loads [22–27], as well as during structural operation under extremely low temperature conditions [28]. In options where the number of welds is minimized, the necessity to use complex cast elements arises. Therefore, to ensure the reliable operation of connections, it is essential to reduce the number of welds and perform them as complete-joint-penetration (CJP) welds exclusively under controlled factory conditions, which will significantly increase the operational reliability of the entire structure.

A further development of this topic is a new technical solution proposed by Yu.S. Kost in [29], the essence of which involves creating a clamped butt joint along a continuous broken line (meander outline). This line features four vertical segments at the center of each wall of the box-section profile and four horizontal segments extending from the center of one wall to the center of the adjacent wall through the corner of the profile. The butt joint is clamped from all sides by external splice plates using through-bolt high-strength pretensioned bolts. Given the geometry of the joint, under through-clamping, contact pressure develops not only between the splice plates and the profiles but also within the vertical segments of the joint, which enhances its strength and stiffness characteristics. To prevent deformation of the box-section profile walls under the pretension force of the bolts, continuous diaphragms are installed inside the profile

cavity below the horizontal segments of the joint. The geometry of the joint ensures open technological access for welding the continuous diaphragms to the walls of the box-section profile under factory conditions using CJP welds. The number of bolt rows in the joint is four per side, with two rows allocated to each diaphragm, spaced equidistantly from one another. This configuration is necessary because if only one row were allocated per diaphragm, an additional bending moment due to eccentricity would arise within it. Mutually perpendicular bolts are vertically offset from each other to apply the bolt pretension load to the diaphragm without eccentricity. The number of bolts per row is even to ensure symmetry relative to the longitudinal axis of the wall (Fig. 1).

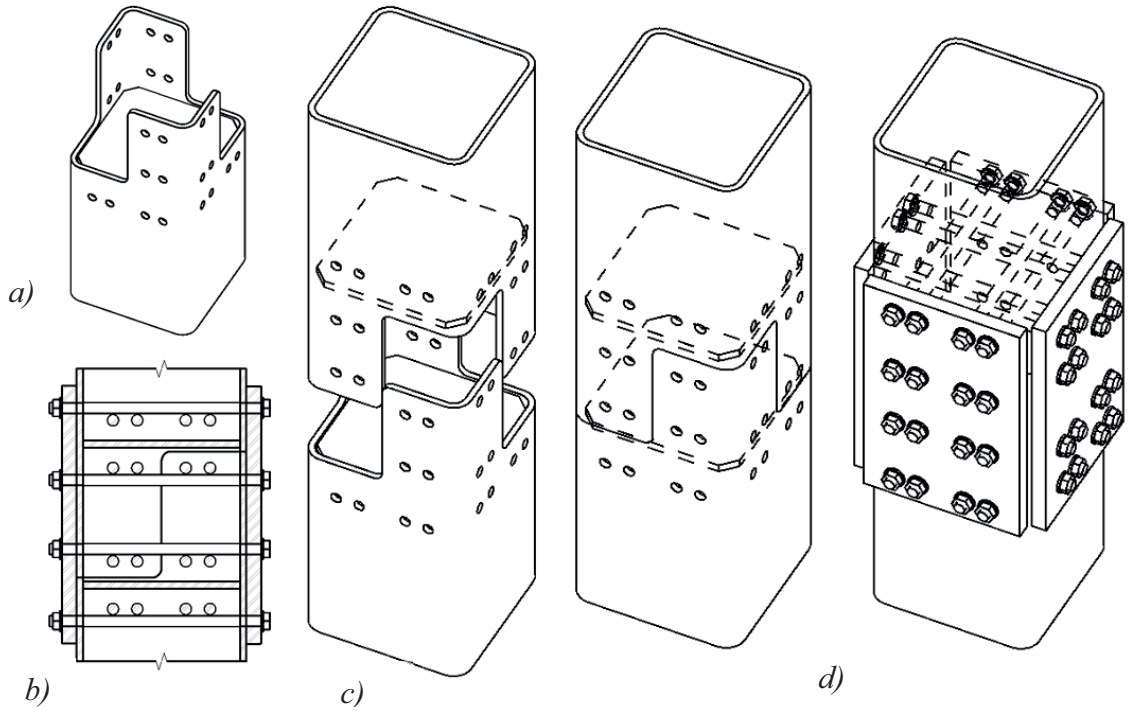


Figure 1. The concept of the butt joint: a – connected box-section profile with a meander outline cutout and installed diaphragm, b – longitudinal section of the joint, c – combining two box-section profiles, d – final assembly of the butt joint using metal plates clamped by through-bolt high-strength pretensioned bolts

Since continuous diaphragm plates are present in the butt joint, it becomes possible to arrange a rigid attachment point for an I-beam beam at the joint location. This can be executed as a bolted unstiffened end-plate connection (BUEEP), in which case the external splice plates become end plates with I-beams welded to them under factory conditions, or as a double-tee moment connection (Fig. 2).

Previously, in [29], the performance of a frame moment connection with a BUEEP and butt joint with meander outline was analyzed based on calculations under seismic impact for a pseudo-plane pinned-base moment frame and a 3-story simply supported moment frame.

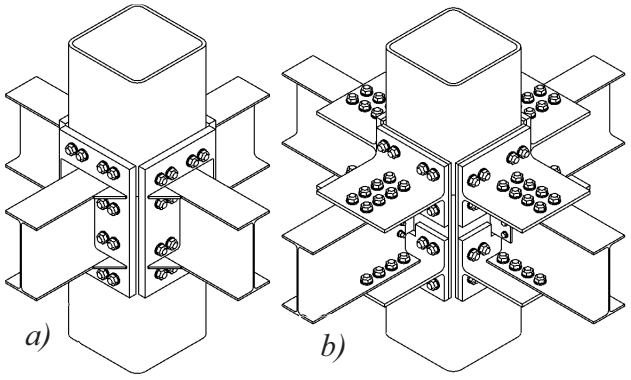


Figure 2. Frame moment connections based on the proposed butt joint: a – BUEEP, b – double-tee moment connection

According to the calculation results, it was revealed that the performance of the butt joint is equivalent to that of a solid profile. Since the concept has proven its viability, it is expedient to conduct further research, and the next stage involves determining the main parameters of a butt joint with meander outline and analyzing the sensitivity of the stress-strain state (SSS) of the connection to these parameters.

METHODS

The main parameters affecting the SSS of the butt joint include:
1) Meander height: high (M) and low (Low M) (Fig. 3);
2) Meander fillet radius (R) (Fig. 4);
3) Number of bolts per row (n), arrangement options, diameter (D), and bolt pretension (N);
4) Splice plate thickness (Fl);
5) Diaphragm thickness (Diaf).

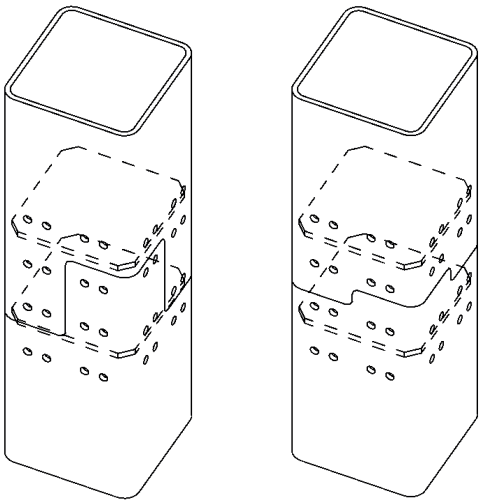


Figure 3. Meander height: a –M, b – Low M

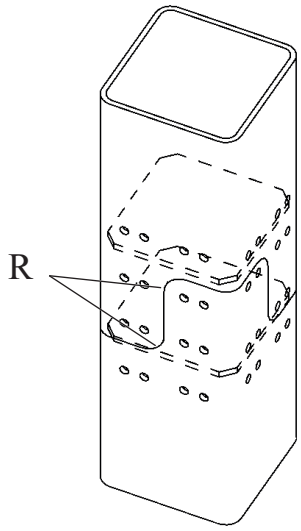


Figure 4. Meander fillet radius

The column wall thickness and the dimensions of the beam elements are not considered in this study, as the profiles of both the column and the beam are determined during the analysis of the entire frame. The column and beam profiles are adopted based on the structural design results of the steel frame under seismic loading in compliance with regulatory codes. Since this work investigates an idealized joint concept, the tolerances for gaps between the elements and bolt holes are assumed to be zero. Calculations are performed using ANSYS software, taking into account both material and geometric nonlinearities under a bending moment load that induces a plastic hinge within the beam. Structural steel (C345) is defined by a multilinear kinematic hardening model, except for the bolts, which are modeled without material nonlinearity. The friction coefficient for unilateral contacts is set to 0,2. Within each parameter combination, identical finite element (FE) mesh and time-stepping settings are applied. The numerical analysis is divided into several stages, each evaluating the influence of the parameters as a function of the bolt pretension force.

RESULTS AND DISCUSSION

The first stage involves evaluating the influence of the *meander height* and *fillet radius*. The primary column (GOST 32931-2015) and beam (GOST R 57837-2017) combination is designated as 350×13 / 30Б1. Since beam cross-sections vary along the height of the frame to ensure

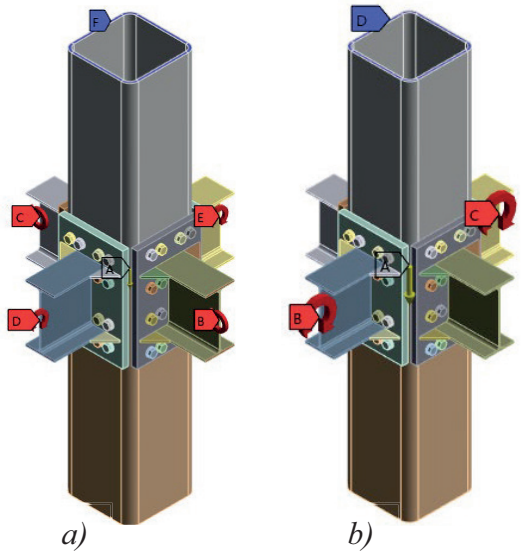
proper plastic hinge formation, the 350×13 / 25Б1 combination is also considered. Additionally, to account for a potential scenario where the column is underdesigned, the 350×13 / 35Б1 combination is analyzed, in which the plastic hinge develops later. In turn, each combination is modeled under two loading schemes (Fig. 5):

1) Diagonal loading, where a bending moment is applied to each beam, causing column bending outside its principal axes;

2) Direct loading, where a bending moment is applied to two beams located along a single straight line, causing column bending within its principal axes.

A common feature for all combinations is the beam-to-column connection via a 30-mm thick flange using eight M20 bolts per beam flange. The bolt hole diameter is equal to the bolt diameter (zero-tolerance holes), and 13-mm thick internal diaphragm plates are installed at the level of the beam flanges.

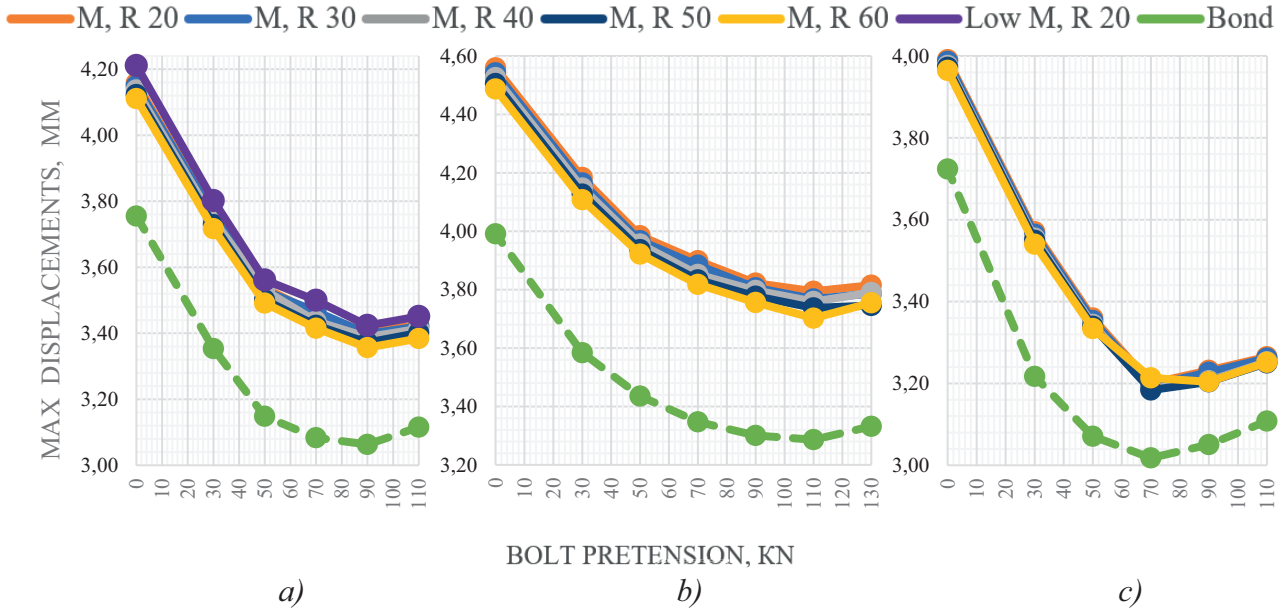
Since numerous variants of the designated parameters must be evaluated for each combination option, a single comprehensive indicator is required to describe the overall connection performance with a single value.



a) *b)*

Figure 5. Loading schemes of the first stage: a – diagonal loading, b – direct loading

In this study, maximum total displacements within the connection are the most suitable criteria (Figs. 6–7). For comparative purposes, a baseline variant featuring a solid profile instead of a butt joint was introduced.



a) *b)* *c)*

Figure 6. Maximum displacements in joints of diagonal combinations: a – 350x13/30Б1, b – 350x13/35Б1, c – 350x13/25Б1

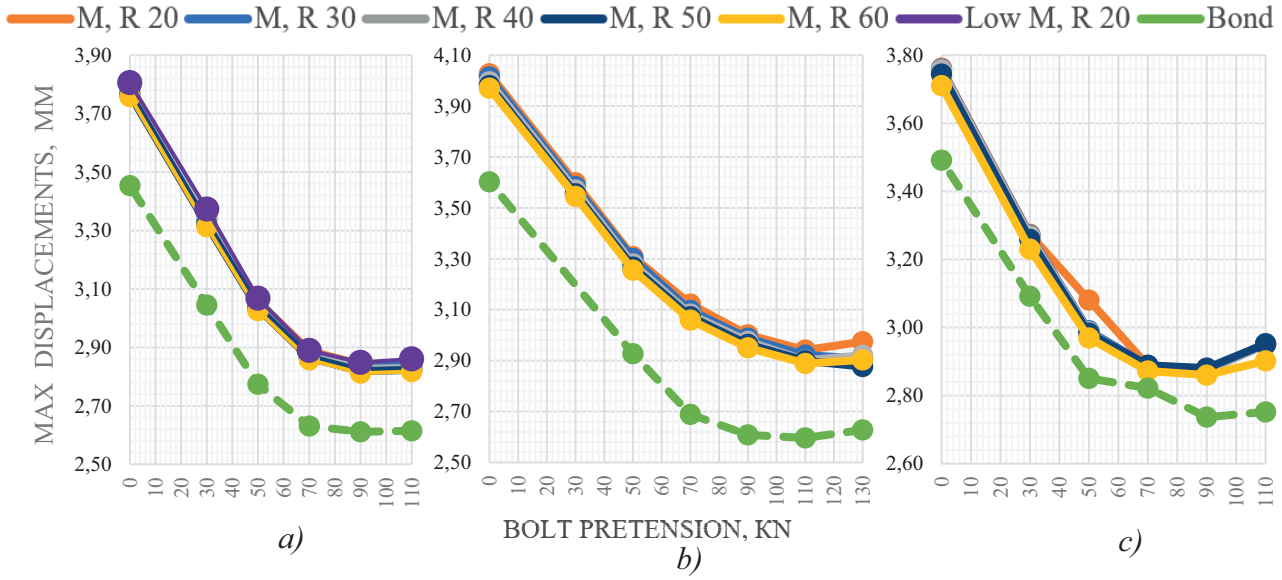


Figure 7. Maximum displacements in joints of direct combinations: a – 350x13/30Б1, b – 350x13/35Б1, c – 350x13/25Б1

Regarding bolt pretension:

1) To achieve maximum stiffness, a specific pretension force value is required; however, excessive clamping (over-clamping) results in a reduction in connection stiffness;

2) The meander height and fillet radius do not affect this required pretension value;

3) Larger beam sections and higher bending moments require a greater pretension force to achieve higher stiffness; however, this effect is not critical, as a pretension range of 50–110 kN provides a sufficient clamping effect for all analyzed cases.

Regarding meander height:

A low meander height adversely affects connection stiffness; furthermore, from a structural standpoint, fabricating such a butt joint is not feasible in all scenarios (e.g., when utilizing smaller beam cross-sections). Consequently, it is impractical to consider it in subsequent parameter combinations.

Regarding meander fillet radius:

A larger radius provides higher stiffness, though this effect is not critical, particularly for the 25Б1 beam combination. In all analyzed cases, a connection with a bolt pretension force of 50 kN or higher exhibits greater stiffness than a solid profile without clamping. The strain distribution is illustrated in Fig. 8, using the 350×13 / 35Б1-M-R60-N110 combination as an example

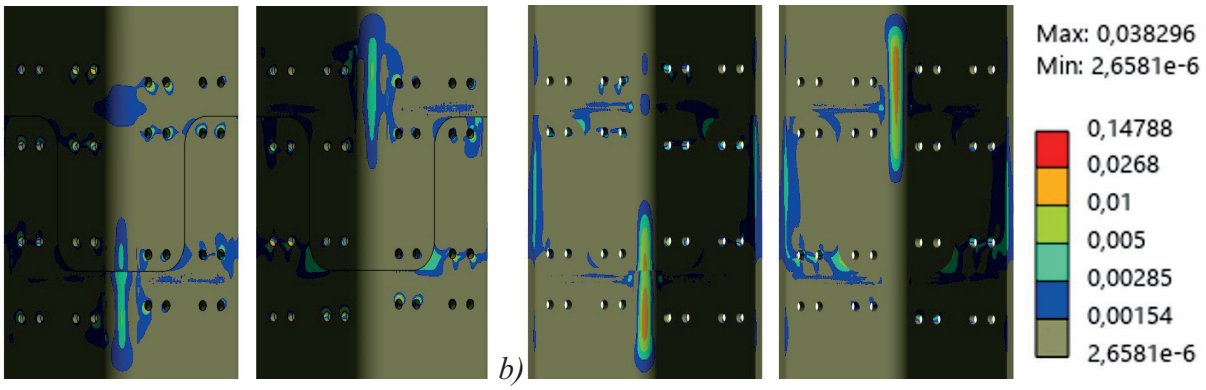


Figure 8. Equivalent total strain of diagonal combinations 350x13/35Б1-M-R60-N110: a – external surface of the profile, b – inside the profile cavity

Maximum strains in the elements reach the steel strain-hardening stage only within the zones of the bolt holes, amounting to 3.82%.

The second stage evaluates the influence of *bolt diameter, number of bolts per row*, and *arrangement options*. The analyzed combination is identical to the baseline 350×13 / 30Б1 configuration from the first stage under the diagonal loading scheme, with variations in reducing the number of bolts from eight to four per beam flange and increasing their diameter from 20 mm to 30 mm. A comparison was made with the results of the first stage. Since fewer bolts were used in the connection, more space became available for their placement. This allows for shifting them closer to the beam centerline (Option 1) or closer to the column web (Option 2) (Fig. 9).

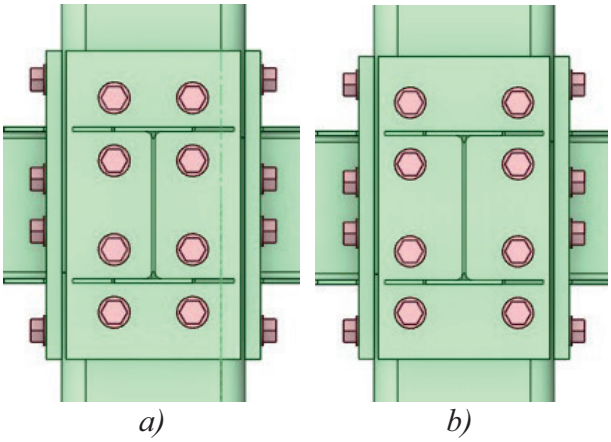


Figure 9. – Bolt arrangement options: a – option 1, b – option 2

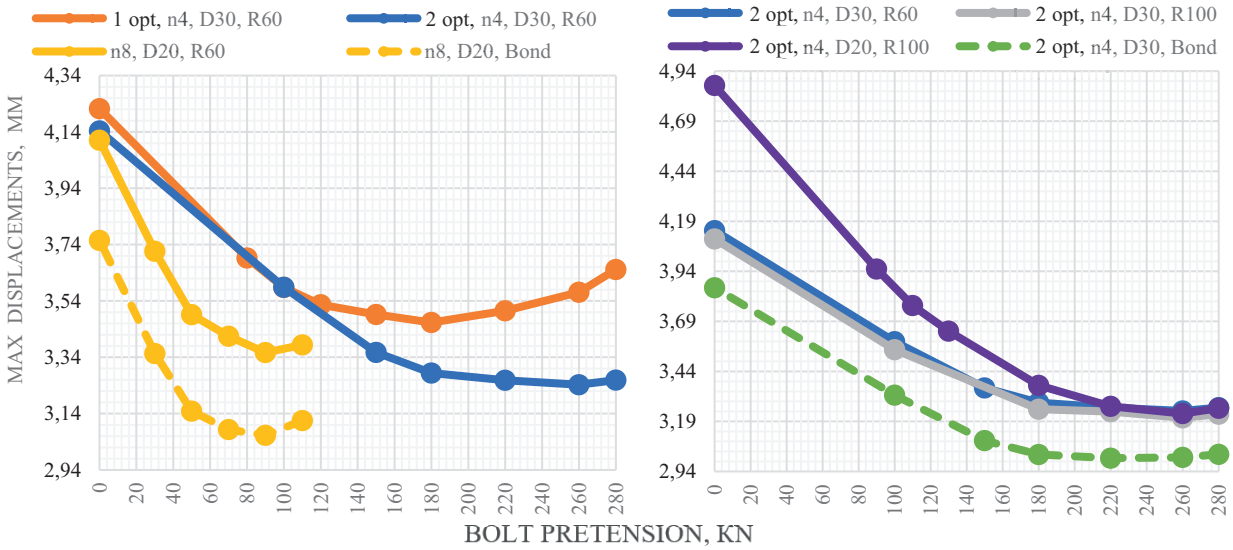


Figure 10. Maximum displacements in joints of combination 350x13/35Б1 depending on the number of bolts per row, their position and diameter

Positioning the bolts further from the profile webs reduces the pretension efficiency and fails to achieve the same stiffness level as the alternative option. Replacing eight bolts with four exhibited no adverse effects on the connection in terms of either stiffness or strength. However, it requires approximately a twofold increase in the bolt pretension force, which induces severe plastic strains exceeding 5% within the zones of the profile holes. Reducing the number of bolts and shifting them towards the profile web allows for increasing the meander fillet radius; however, this modification exhibited no effect on the stiffness and strength of the connection. The bolt diameter influences connection stiffness; however, given the required pretension force value, there is no difference between different diameters (Fig. 10).

Similar results are obtained for the 500×18.5 / 45Б1 combination, where the beam is connected to the column via a 30-mm thick flange using eight M30 bolts per beam flange and 16-mm thick diaphragm plates (Fig. 11).

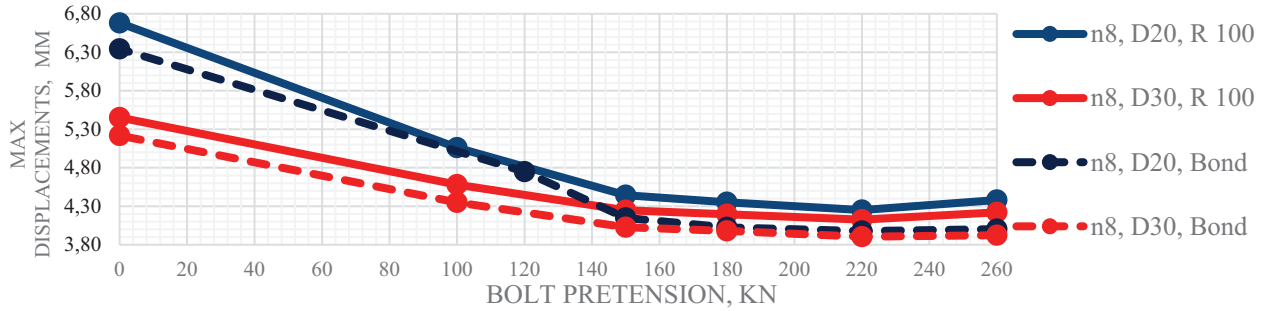


Figure 11. Maximum displacements in joints of combination 500x18,5/45Б1 depending on diameter of bolts

The third stage evaluates the influence of the *splice plate thickness* and the *diaphragm thickness*. The combinations from the previous stages are adopted: 350×13 / 30Б1 and 500×18.5 / 45Б1. The splice plate thickness is analyzed ranging from 20 to 35 mm in 5-mm increments (Fig. 12).

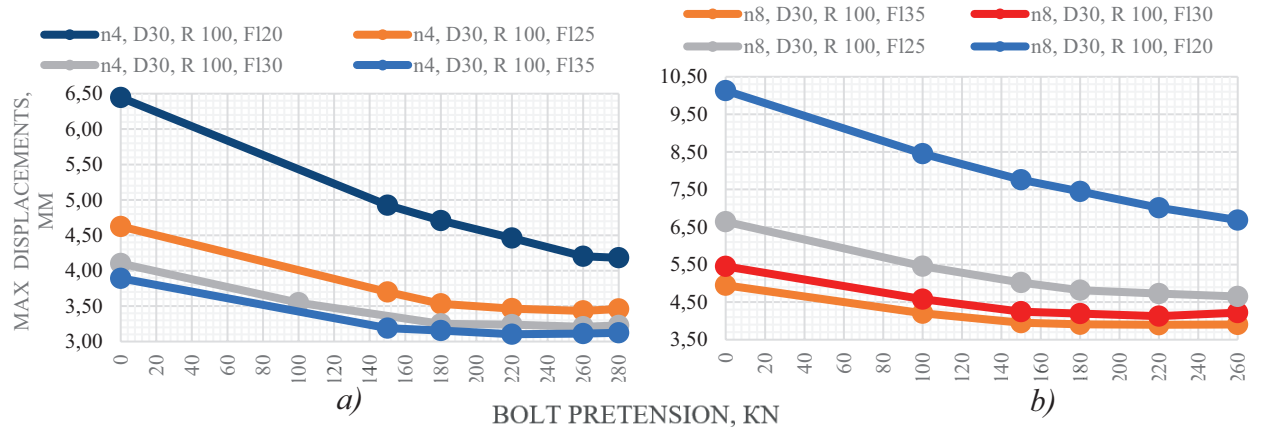


Figure 12. Maximum displacements in joints depending on splice plate thickness of combination: a – 350x13/30Б1, b – 500x18,5/45Б1

As the splice plate thickness decreases below 30 mm, an exponential increase in joint displacements is observed, along with a shift toward higher optimal pretension force for maximum stiffness and a linear increase in diaphragm strains. Depending on the diaphragm thickness, the following results are obtained (Fig. 13).

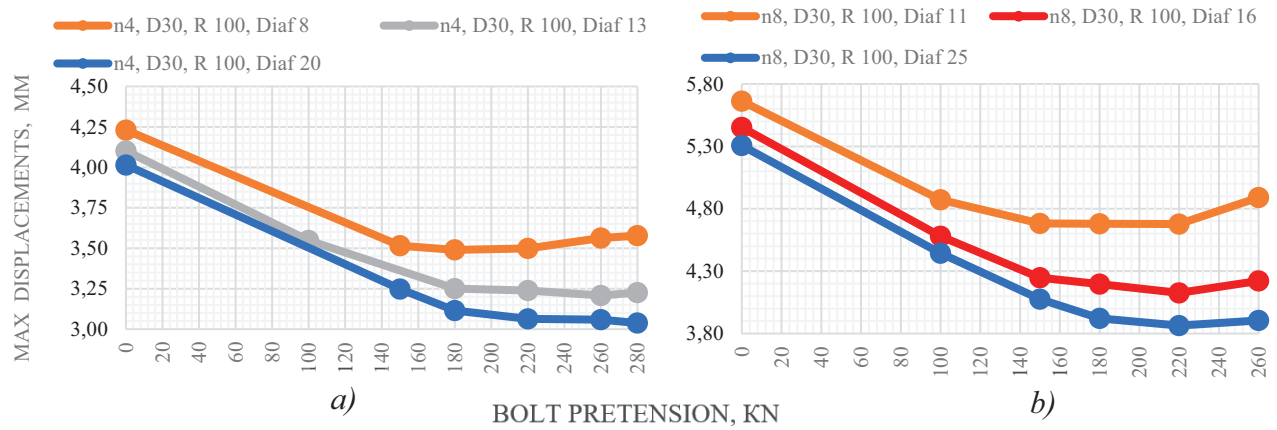


Figure 13. Maximum displacements in joints depending on diaphragm thickness of combination: a – 350x13/30Б1, b – 500x18,5/45Б1

The analysis indicates that a diaphragm thickness exceeding 1.5 times the beam flange thickness has a negligible effect on joint SSS, higher thicknesses reduce strains in the splice plates. Sensitivity analysis results, including these findings, are summarized in Table 1.

Table 1. – Summary of SSS sensitivity analysis regarding joint parameters

№	Parameters	Influence trend	Recommendation / Critical threshold
1	Meander height	Direct relationship: high height → high stiffness. Low height reduces stiffness performance.	Use the high variant; exclude the low variant from consideration
2	Meander fillet radius	Moderately positive effect on element strength and overall stiffness (minor)	Adopt the maximum possible value within structural requirements
3	Bolt pretension	Nonlinear: stiffness increases up to a certain limit, followed by a decrease due to plastic deformations	Determined by numerical simulation
4	Bolt arrangement options	Shifting towards the box-section profile webs increases bolt pretension efficiency and overall stiffness	Position as close as possible to the outer profile webs
5	Number of bolts per row and diameters	Influence is negligible, provided that the required total clamping force is ensured	Reducing the number of bolts per row is acceptable, provided that the bolt pretension force is increased
6	Splice plate thickness	High impact: exponential increase in displacements at thicknesses < 30 mm	Recommended value for the first iteration is 30 mm
7	Diaphragm thickness	Reduction in splice strains and negligible effect on overall stiffness at thicknesses > 1.5 times the I-beam flange thickness	Adopt ≈ 1.5 times the I-beam flange thickness

Thus, it was revealed that:

1) Regarding geometric parameters, it was established that the meander height is a defining factor: low height values not only reduce the overall stiffness of the connection but also create technological constraints during the installation of small-section beams. Meanwhile, the transitional fillet radius exerts a moderately positive effect on the strength of individual elements by preventing stress concentration; however, its impact on the overall stiffness of the butt joint is secondary

2) Regarding pretension force, the analysis revealed a nonlinear relationship between the bolt pretension value and connection stiffness. There is a critical clamping threshold beyond which a reduction in stiffness is observed due to the development of significant plastic strains. Furthermore, it was found that the pretension efficiency directly depends on the bolt positioning: shifting them away from the profile web reduces the overall structural stiffness. The number of bolts does not exert a significant influence on the joint SSS, provided that the pretension force in each element is proportionally increased. The optimal bolt pretension value is determined by numerical

simulation, highlighting the necessity to develop an analytical formula for its calculation
3) Regarding the influence of structural elements, it was revealed that joint exhibited the highest sensitivity to the beam splice plate thickness: at values below 30 mm, an exponential increase in joint displacements is observed, along with a shift of the optimal bolt pretension point toward higher values. Meanwhile, the profile diaphragm thickness exerts a minimal effect on the overall stiffness at thicknesses exceeding 1.5 times the I-beam flange thickness; however, it contributes to reducing splice plate strains.

CONCLUSION

The main parameters of a butt joint with meander outline were determined, and a sensitivity analysis of their impact on the joint SSS was conducted. Based on the data obtained, recommendations were provided for designing the optimal configuration of a rigid frame moment connection joining a box-section column and an I-beam beam with a minimal number of factory-executed welds. The present study is a continuation of the research on this butt joint [29] and concludes the analysis of its idealized concept. The next stage of the research will focus on adapting this idealized joint concept into an engineering model that accounts for manufacturing tolerances regarding the cutout execution and component mating. This will enable the final classification of the bolted connection based on its behavior and load transfer mechanism.

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