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

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Abstract: A steel moment frame is a design solution that effectively withstands seismic impact. In National Standards of various countries, box-section columns are recommended for use in moment frame, while this requirement is mandatory in the Russian Federation. Therefore, it is necessary to have a frame moment connection between an I-beam and such column. Most existing solutions involve many welds which reduce reliability under dynamic loads or low temperature conditions. Solutions with fewer welds require special cast components. This article proposes a solution to this problem by introducing a butt joint for box-section columns that creates a frame moment connection with minimal welds, without using any special cast components, and complies with the requirements of National Standards on earthquake-resistant construction in Russia.

Based on calculations performed in ANSYS for extracted frame moment connection in static formulation as well as pseudo-plane single-story moment frame and multi-story moment frame in dynamic formulations using accelerograms from earthquakes, a comparative analysis was conducted regarding stress-strain state of the frame moment connection without butt joints and with different types the outline of butt joints.

It has been found that a butt joint with the outline like a meander is equivalent to a solid column without cutout, allowing calculations of entire design model without detailed modeling of the frame moment connection, simply by applying fixed joint of column and beam. Additionally, one advantage of this type of butt joint is its ability to solve the issue of installing diaphragm plates in the box-section column body.

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

СТЫК С ОЧЕРТАНИЕМ МЕАНДРА КОРОБЧАТОЙ КОЛОННЫ ДЛЯ СЕЙСМОСТОЙКОГО РАМНОГО УЗЛА

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Аннотация: Стальной рамный полный каркас представляет собой конструктивное решение, которое эффективно воспринимает сейсмическое воздействие. В национальных стандартах различных стран для полных рамных каркасов рекомендуется применять колонны коробчатого профиля, а в Российской Федерации это требование является обязательным. В связи с этим необходим жёсткий узел крепления ригеля из двутавра к такой колонне. В большинстве существующих решений присутствует много сварных соединений, которые снижают надежность конструкций при динамическом воздействии или эксплуатации в условиях низких температур, а в тех, где сварных соединений мало, необходимо использование специальных литых деталей. Предложено решение данной проблемы в виде стыкового соединения колонн коробчатого сечения, позволяющее в месте стыка создать жёсткий рамный узел с минимальным количеством узлов, без специальных литых деталей и соответствующий требованиям нормативных документов в области сейсмостойкого строительства Российской Федерации.

По результатам расчёта в ANSYS вырезанных узлов в статической постановке, а также псевдо-плоской одноэтажной рамы и многоэтажного полного рамного каркаса в динамической постановке по акселерограммам землетрясений, был проведён сравнительный анализ напряженно-деформированного состояния рамного узла без стыка и со стыками разного очертания.

Было выяснено, что стык с очертанием меандра эквивалентен цельной колонне без разреза, что даёт возможность проводить расчеты всей схемы каркаса без детального моделирования узла, используя жесткое крепление колонны и ригеля. Помимо этого, к достоинствам такого стыка можно отнести возможность решения проблемы установки поперечных рёбер жесткости в теле колонны коробчатого сечения.

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

INTRODUCTION

Taking into account the fact that certain territories of Russia are seismically active, the design engineer is required to analyze the behavior of the structure from seismic impact. To prevent the collapse of the building frame during a seismic impact, it is necessary to dissipate the energy of the seismic impact, for which you can use both the plastic properties of the material of the load-bearing structures and the use of special seismic base isolation and energy dissipation devices. (1, 2). This may also involve addressing the effects of a "soft story", which could allow improvement of the frame's dynamic parameters or its utilization as an energy dissipation device. (3, 4). However, this approach requires the use of a moment frame in both planes of the column. For these purposes, a steel frame is best suited, which has sufficient strength and the possibility of prolonged residual plastic deformation. In National Standards of various countries, box-section columns are recommended for use in moment frame, while this requirement is mandatory in the Russian Federation. In Russian State Standard SP 14.13330.2018 (including supplement 2-4) the following requirements for the moment frames:

1) The cross section of the columns should be box-section or circular section;
2) diaphragm plates should be installed in the columns at the level of the beam.

Since the column has a closed cross-section, the main design problem is the installation of diaphragm plates in the body of the column.

The existing concepts of design solutions for the frame moment connection of an I-beam and a box-section column used in Russia and abroad can be roughly divided into:

1) Using a welded column (1, 5-11);
2) Using elements as diaphragm plates outside the column cavity (5, 13-15, 18);
3) Using an insert that breaks the column or a butt joint at the level of the upper belt of the beam (5, 12, 16-17);
4) The use of special cast components (6, 18-21)

Most existing solutions involve many welds which reduce reliability under dynamic loads (22-27) or low temperature conditions (28). Solutions with fewer welds require special cast components. Since the Russian State Standard does not prohibit the butt joint of columns at the place where the beam is attached, a butt joint of box-section column is considered in this work (with different cut shapes), which makes it possible to create a frame moment connection beam attachment unit at the butt joint that meets the requirements of Russian State Standard of earthquake-resistant construction of the Russian Federation. The essence of the butt joint is to reduce the welds in the moment frame of the I-beam and box-section column. It is assumed that such a column will be made of hot rolled square pipe and, due to this, it will be possible to do only factory full penetration weld joints of diaphragm plates, which will increase the reliability of the structure. (fig. 1).

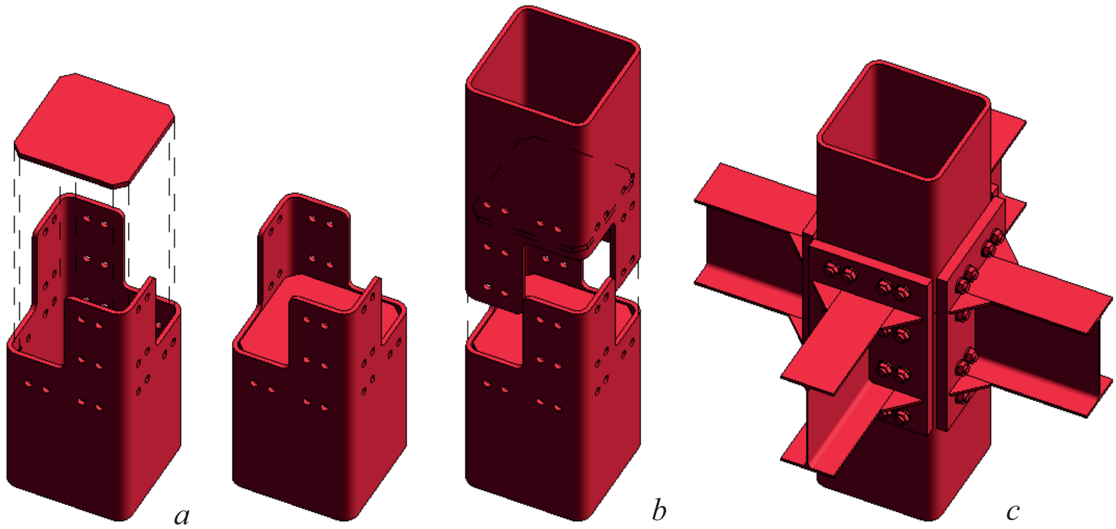

Figure 1. The concept of the butt joint and the frame moment connection whole: a – a jointed square pipe with a meander-shaped trim and a place where the diaphragm plates, b – combining two square pipe, c – the final assembly of the butt joint and the frame moment connection as a whole using metal plates and (or) beam flanges, tightened with pretensioned studs or bolts passing through the profile

METHODS

To obtain reliable data on the behavior of the frame moment connection an earthquake, it is necessary to calculate the entire structure using solid finite elements (hereinafter FE) using an accelerogram, with physical and geometric nonlinearity in time. Such a task is quite resource-intensive. In addition, increased control is needed at the level of the source data assignment. To avoid possible errors, the calculation should begin with a simple analysis of the frame in a linear formulation using the Response Spectrum Analysis (hereinafter RSM) without modeling frame moment connection, and then gradually complicate it.

RESULTS AND DISCUSSION

The first example – a pseudo-flat single-story pivotally supported 5x5 m frame, fixed from the bottom of the plane in the column heads (fig.2). The columns are made from 250x8 rolled square pipe according to Russian State Standard GOST 32931-2015, and the beam is made from a 20Ш2 I/H-beam according to Russian State Standard GOST R 57837-2017.

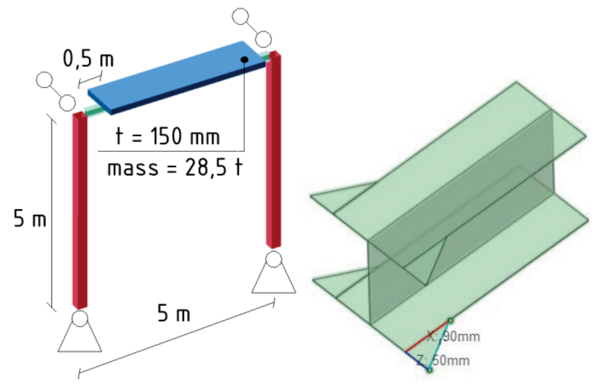

Figure 2. Scheme of pseudo-flat single-story frame and shell moment connection sections

At a distance of 0.5 m from the column, a monolithic reinforced concrete floor slab is fixed attached to the beam, which will not allow the beam to buckling failure. A plastic hinge is expected in the beam. In addition to its own weight of the structure, a uniformly distributed mass of 28.5 tons is applied to the beam. The scheme consists of beam elements, with the exception of the shell support parts of the 0.5 m long beam with additional shelf widening.

Step 1 consists in determining the maximum bending moment in the columns, total deformation and base shear without modeling the frame moment connection, representing it as a fixed joint, from a given artificial single-component accelerogram with a damping coefficient of 0.027. The material of steel structures is S345 steel, set by multilinear kinematic hardening model (fig.3). The calculation is carried out by direct integration of equation of motion in time into ANSYS Transient with geometry and physical linear and nonlinear, and also RSM in ANSYS Response Spectrum from response spectrum plot based on accelerogram. The results are shown in the figures 4-6.

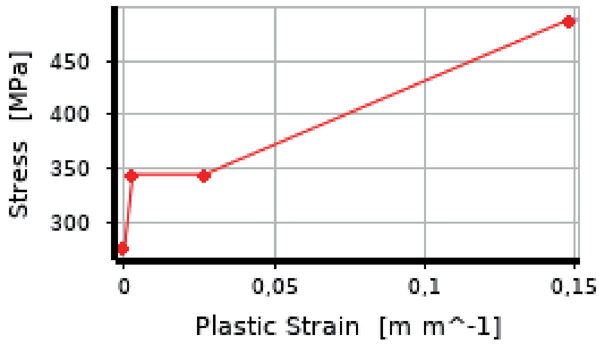

Figure 3. Chart of properties row S345 at multilinear kinematic hardening

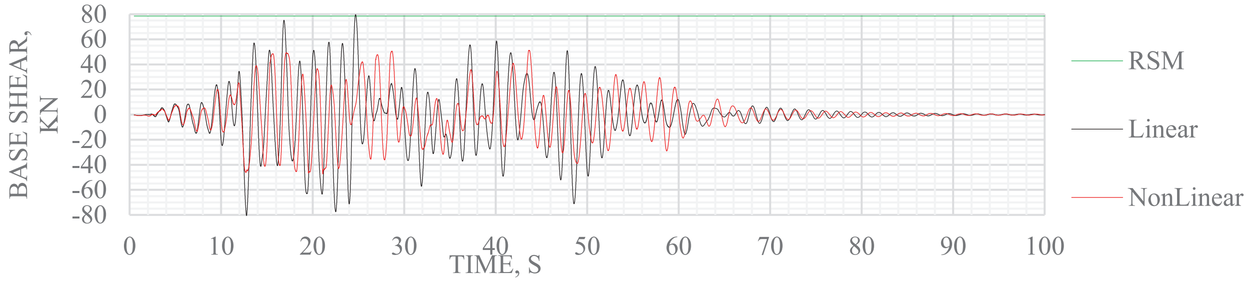

Figure 4. Base shear single-story frame without modeling the frame moment connection

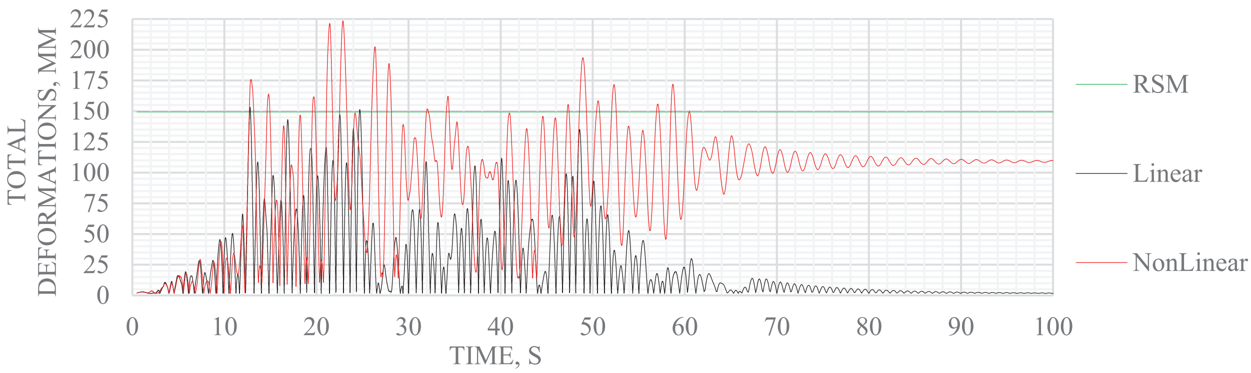

Figure 5. Total deformations single-story frame without modeling the frame moment connection

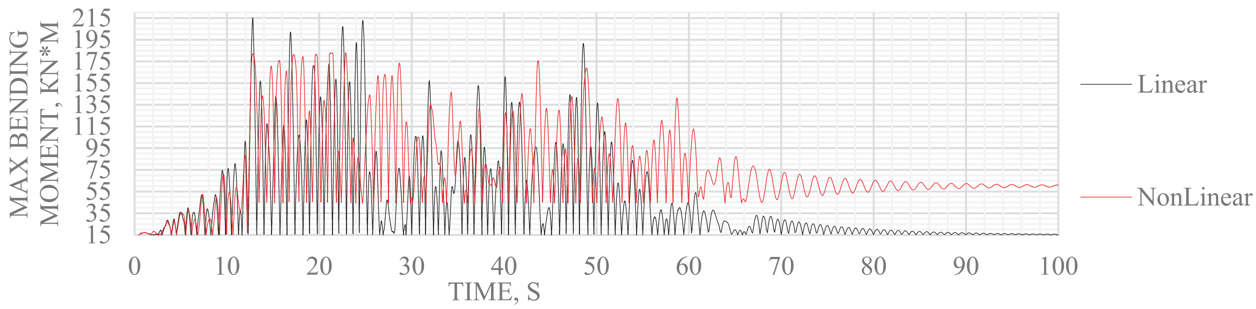

Figure 6. Maximum bending moment in the columns single-story frame without modeling the frame moment connection

Based on the calculation results, the following conclusions can be drawn:

1) Linear calculation in time and RSM have almost identical results with an inaccuracy of about 1–2%. This indicates that the integration step and the Relay damping coefficients are set correctly;

2) In the nonlinear calculation, the base shear decreased by 0.65 times, the maximum bending moment in the columns by 0.85 times, and the total deformation increased by 1.46 times. A decrease in bending moment and base shear indicates that a plastic hinge appeared in the frame, which dissipated seismic energy, and an increase in deformation means that strong residual deformations occurred in the frame and the deformed frame further perceived the seismic impact;

3) In the nonlinear calculation, the maximum stress in the columns is 328 MPa, therefore, the plastic hinge occurs only in the beam.

Step 2. Before modeling solid-state frame moment connection for dynamic calculation, it is worth checking the suitability of their different variants by static calculation.

Common to all considered joints is the connection of the beam to the column via a 25-mm-thick flange using M16 studs with a pretension force of 90 kN. Diaphragm plates are installed internally at the level of the beam's flanges. The results are shown in the table 1.

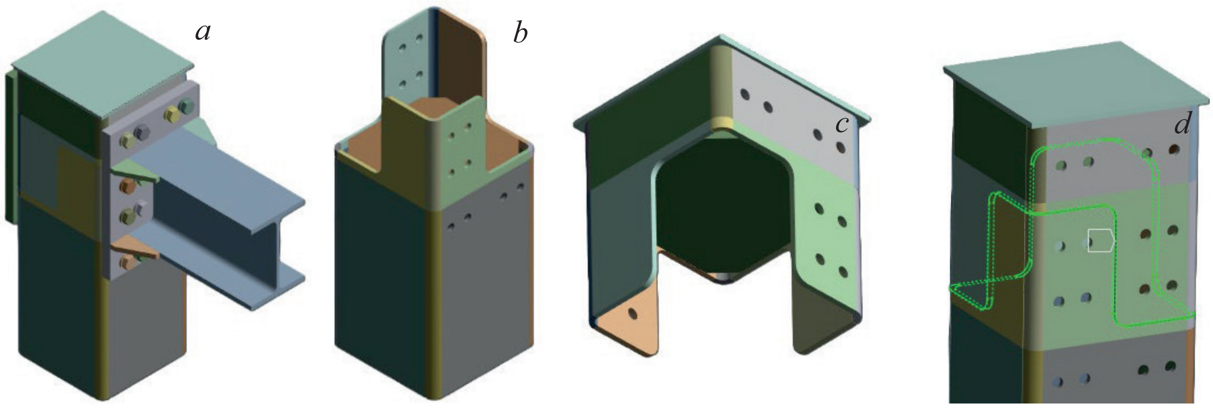

Figure 7. *1 variant. Column with the meander outline: a – assembled butt joint, b-c – jointed parts, d – outline of the cut*

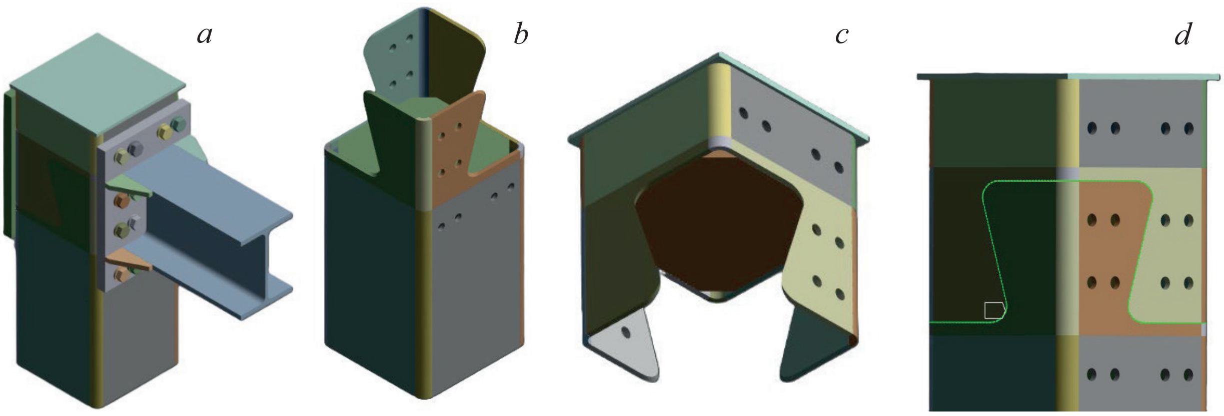

Figure 8. *2 variant. Column with a through-cut along the path: a – assembled butt joint, b-c – jointed parts, d – outline of the cut*

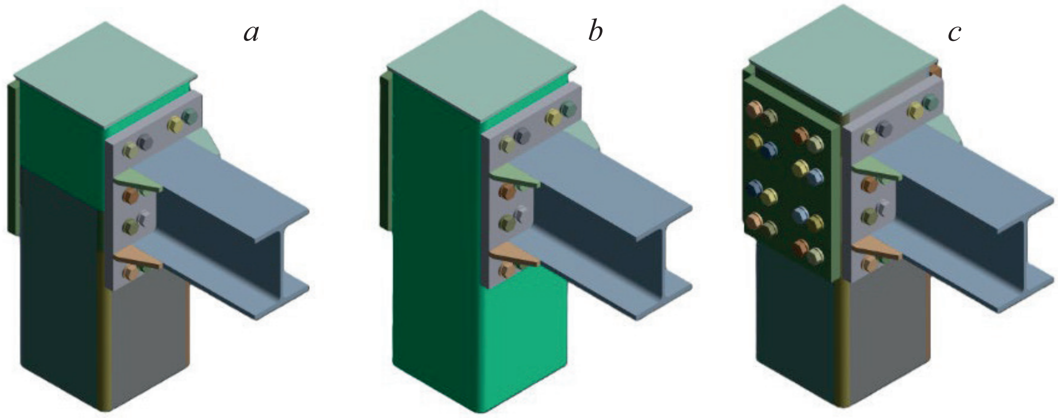

Figure 9. 3-7 variants: a – 3 variant with a cut in the center, b – 4 the uncut variant, c – 5-7 variants (accordingly, 1-3 variants with the addition of side plates, flange thickness)

Table 1. The results of the static calculation of the variants of the head frame moment connection with a load on the beam 135 кN·m.

N	Butt joint Description	Total deformation, mm	Max equivalent plastic strain, mm/mm	Max equivalent stress in studs, MPa
1	Meander outline	27,25	0,198	2412,6
2	Through-cut along the path	35,17*	0,434*	3061,2*
3	Cut in the center	56,78	0,312	4530,3
4	Uncut	8,07	0,018	941,5
5	Meander outline with the addition of side plates	8,36	0,020	1182,5
6	Through-cut along the path with the addition of side plates	8,58	0,027	1359,8
7	Cut in the center with the addition of side plates	9,59	0,053	1043,0

*The * sign means that there is no convergence on 135 кN·m, the values are shown on 121,5 кN·m*

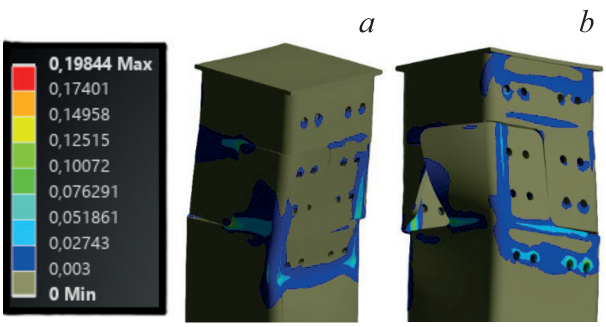

Figure 10. Equivalent plastic strain variant 1: a – front, b – rear

Variants 2-4 clearly demonstrate how different types of cutouts affect the work of joints without side plates. Variant 1 turned out to be the best, since in any direction of the bending moment there will be resistance to bending by one wall of the column.However, even with it, the maximum equivalent plastic strain go beyond the temporary resistance of steel. Variants 5-7, due to the additional plates, are already showing satisfactory performance. In terms of stiffness and strength parameters, variant 5 is closest to variant 4.

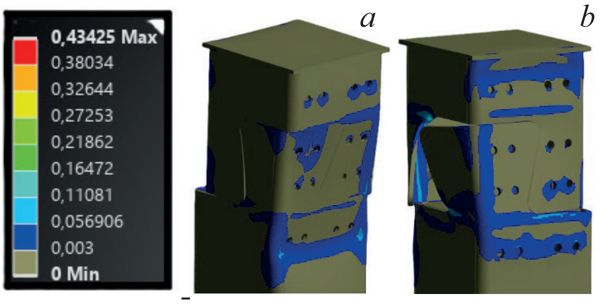

Figure 11. *Equivalent plastic strain variant 2: a – front, b – rear*

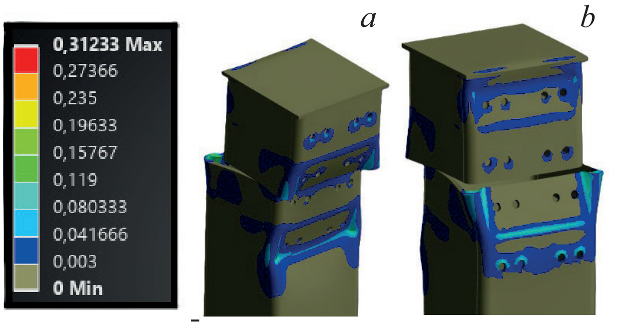

Figure 12. *Equivalent plastic strain variant 3: a – front, b – rear*

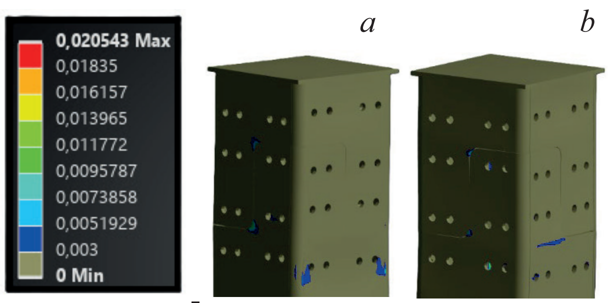

Figure 13. *Equivalent plastic strain variant 5: a – front, b – rear*

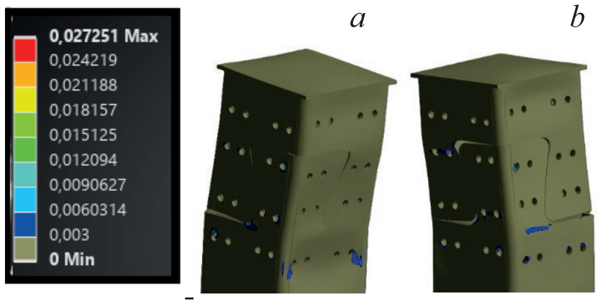

Figure 14. *Equivalent plastic strain variant 6: a – front, b – rear*

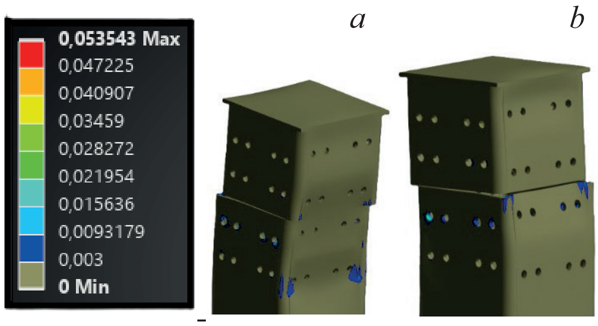

Figure 15. *Equivalent plastic strain variant 7: a – front, b – rear*

Step 3. In order to make sure whether the difference between options 1 and 5 is significant, it is necessary to perform a dynamic calculation. Let's look at 4 cases of frame moment connection modeling:

1) shell FE uncut;
2) solid FE uncut;
3) solid FE with cut meander outline;
4) solid FE with cut meander outline and non-pretensioned studs.

The results are shown in the figures 16-17.

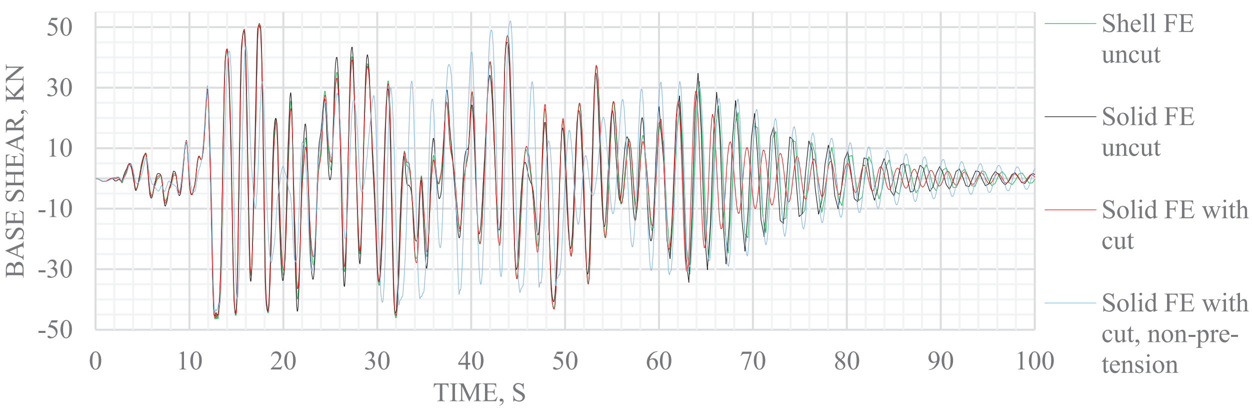

Figure 16. *Base shear single-story frame with modeling the frame moment connection*

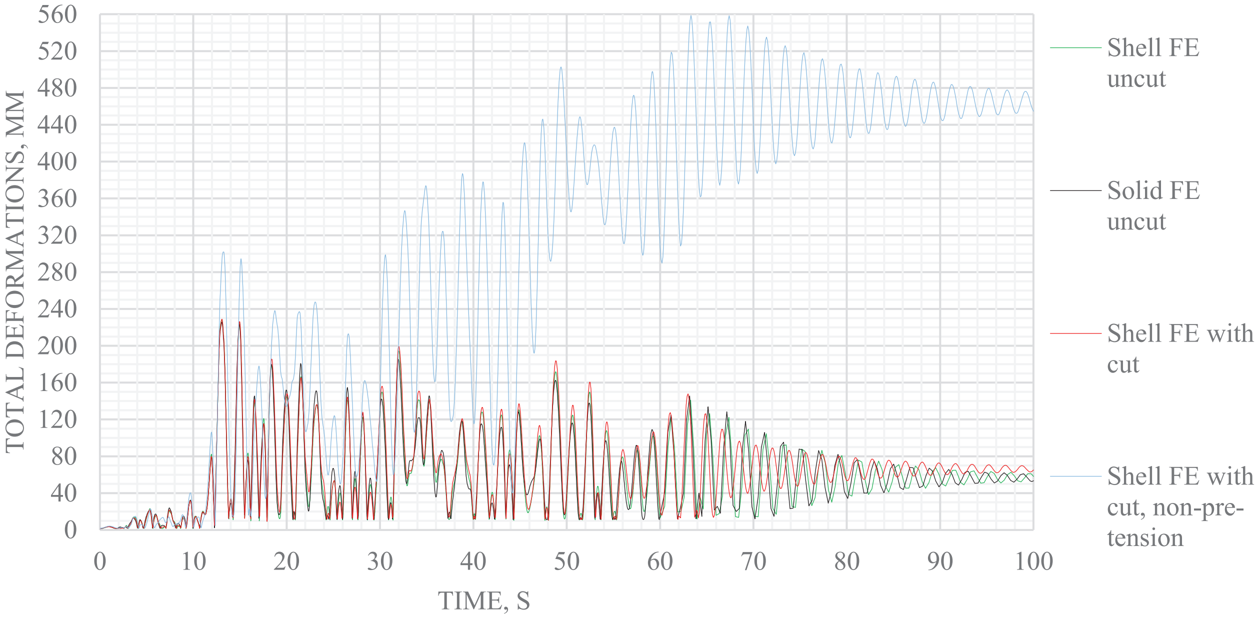

Figure 17. Total deformations single-story frame with modeling the frame moment connection

The graphs show how strongly the pre–tension of the studs affects the stiffness of the connection. The difference in total maximum deformations of 13.07 between solid uncut and with cut is only 1.5%, and, as a result, plastic strain after the earthquake increased by 12%. And with the variant non-pretensioning studs by 13.23 s, the difference is 25.2%, and because of this, the difference in rplastic strain after an earthquake is 793%.

The first example demonstrated that the butt joint with meander outline of hot rolled square pipe with 4 plates, compressed with studs a pre-tention force of 90 kN, allows us to create an equally strong joint of a solid pipe and provides the necessary strength and stiffness for a frame moment connection.

Second example – A 3-story hinged frame with a column pitch of 6m and a floor height of 6.6m. The columns are made from 350x13 rolled square pipe according to Russian State Standard GOST 32931-2015, beams of the 1st floor made of I-beam 30Б1 according to Russian State Standard GOST R 57837-2017, 2nd floor made of I-beam 25Б1, 3rd floor made of I-beam 20Б1. At a distance of 0.5 m from the column, a monolithic reinforced concrete floor slab is fixed attached to the beam. A plastic hinge is expected in the beam. In addition to its own weight of the structure, a uniformly distributed mass of 350 kg/m^2 is applied to the slab (fig. 18).

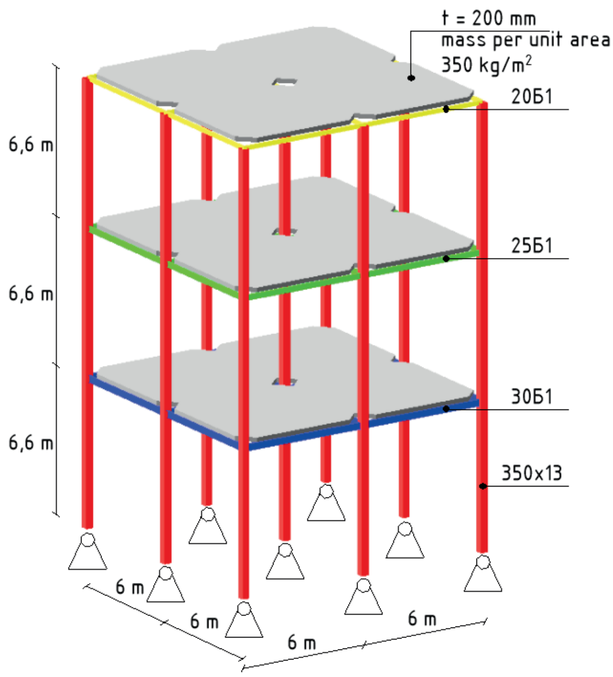

Figure 18. – Scheme of multi-story frame

Step 1. Calculations are performed similarly to the first example, but using a three-component accelerogram of a real earthquake. The results are shown in the figures 19-23.

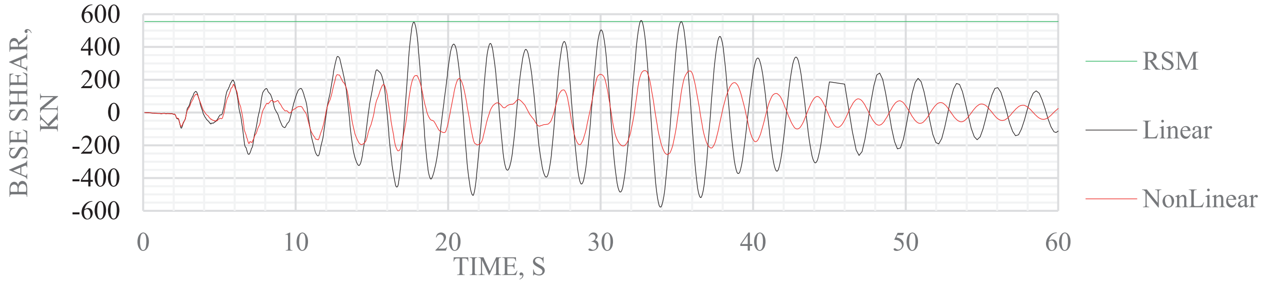

Figure 19. *Base shear multi-story frame in longitudinal direction without modeling the frame moment connection*

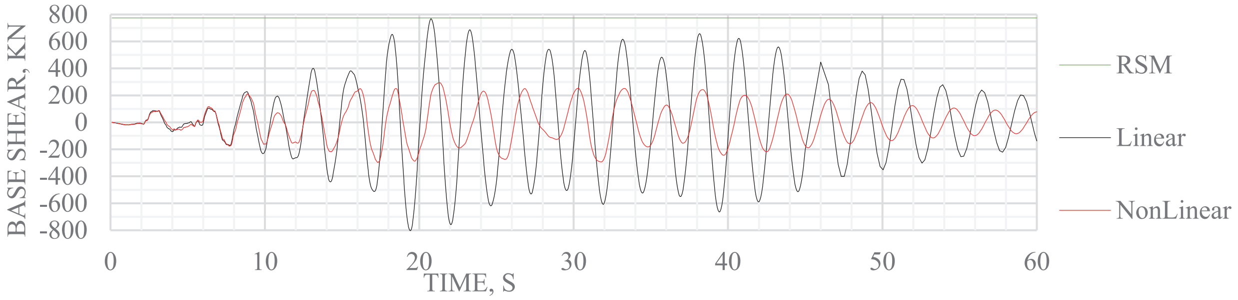

Figure 20. *Base shear multi-story frame in transverse direction without modeling the frame moment connection*

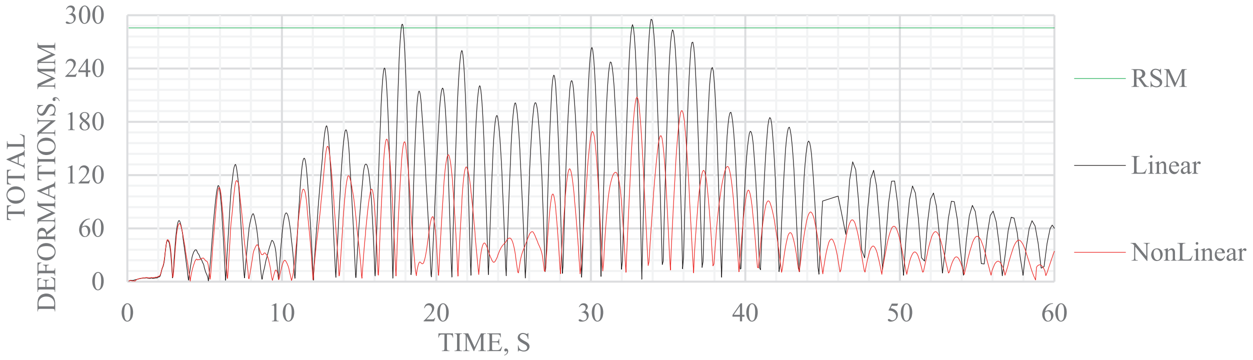

Figure 21. *Total deformations multi-story frame in longitudinal direction without modeling the frame moment connection*

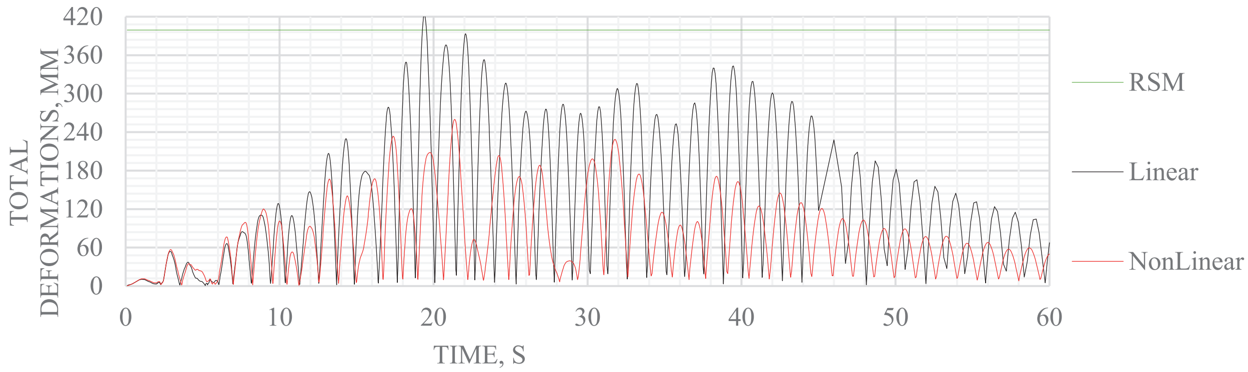

Figure 22. *– Total deformations multi-story frame in transverse direction without modeling the frame moment connection*

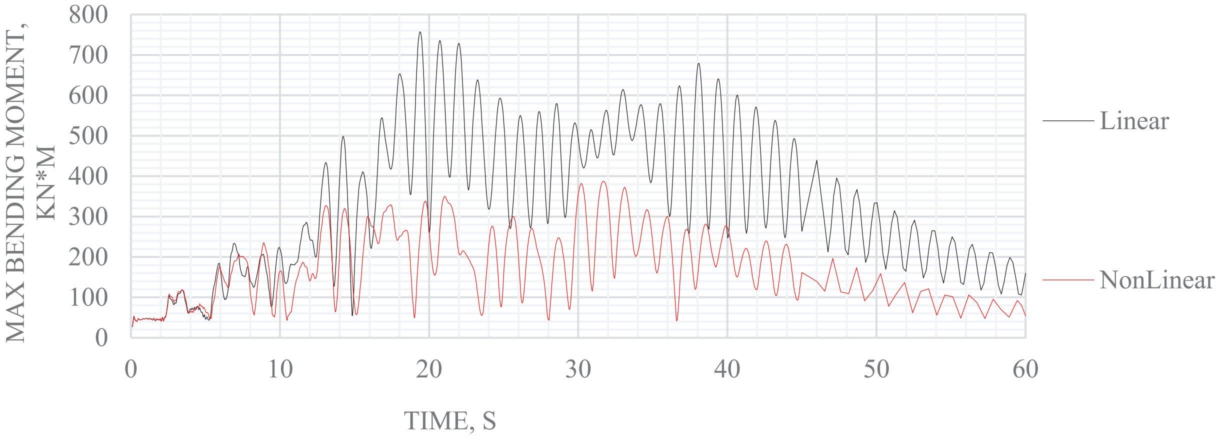

Figure 23. Maximum bending moment in the columns multi-story frame without modeling the frame moment connection

Based on the calculation results, we obtain a situation comparable to the previous example, with the exception of:

1) A plastic hinge did not appear in the beam 3rd floor;

2) In the nonlinear solution, base shear decreased by 0.44 times in the longitudinal and 0.36 times in the transverse directions, the maximum bending moment in the columns by 0.51 times, and total deformation of the scheme decreased by 0.53 times.

Step 2. Next, we form solid frame moment connections models and perform their comparison by static calculation in ANSYS Static Structural. Common to all considered joints is the connection of the beam 30Б1to the column via a 30-mm-thick flange using M20 studs with a pretension force of 90 kN. Diaphragm plates are installed internally at the level of the beam's flanges. Two variants are being considered: with one beam and with 4 (fig. 24). The results are shown in the table 2.

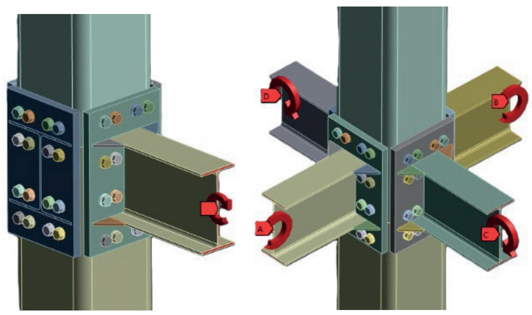

Figure 24. 2 variants solid model frame moment connection

Table 2. The results of the static calculation of the variants of the floor-to -floor frame moment connection with a load on the beam 220 кН ·м

N	Butt joint Description	Total deformation, mm	Max equivalent plastic strain, mm/mm	Max equivalent stress in studs, MPa
1	Uncut, 1 beam	99,86	0,002	704,9
2	Uncut, 4 beams	101,45	0,016	928,6
3	Meander outline, 1 beam	99,25	0,002	718,9
4	Meander outline, 4 beams	102,68	0,033	1533,7
5	Through-cut along the path, 1 beam	99,22	0,004	924,8
6	Through-cut along the path, 4 beams	103,06	0,048	1610,3

Table 2. Continued

7	Cut in the center, 1 beam	99,76	0,003	970,2
8	Cut in the center, 4 beams	103,08	0,044	1650,5

The results show that in the floor-to-floor butt joint, the results are generally comparable with each other, but variant with a Meander outline is closer to the not cut variant.

Step 3. Calculate the entire frame using a solid model with a meander outline.

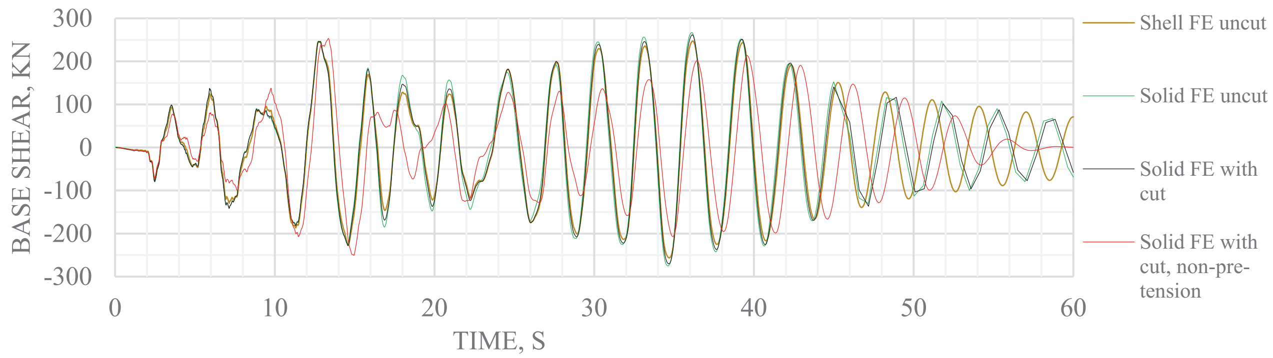

Figure 25. Base shear multi-story frame in longitudinal direction with modeling the frame moment connection

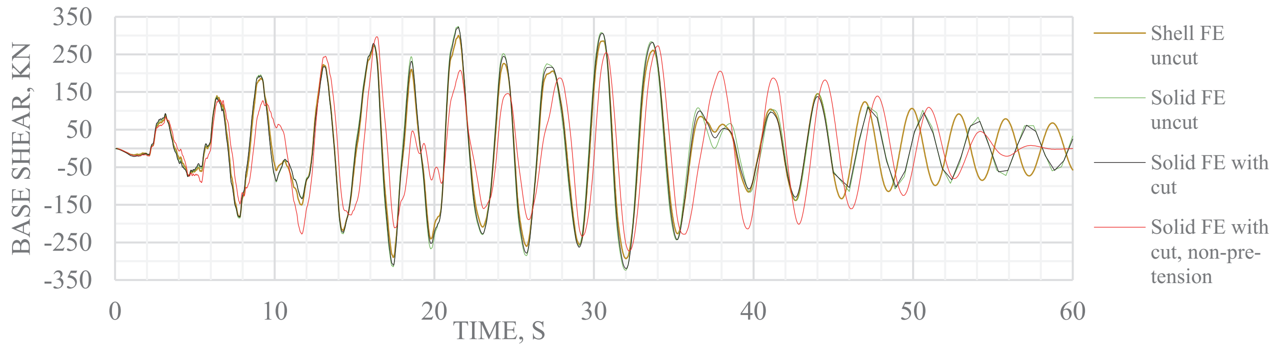

Figure 26. Base shear multi-story frame in transverse direction with modeling the frame moment connection

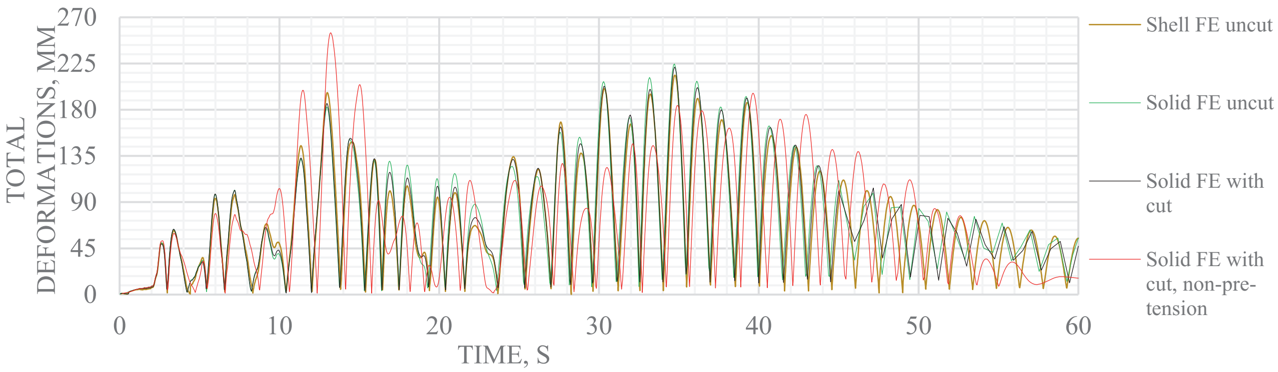

Figure 27. Total deformations multi-story frame in longitudinal direction with modeling the frame moment connection узла

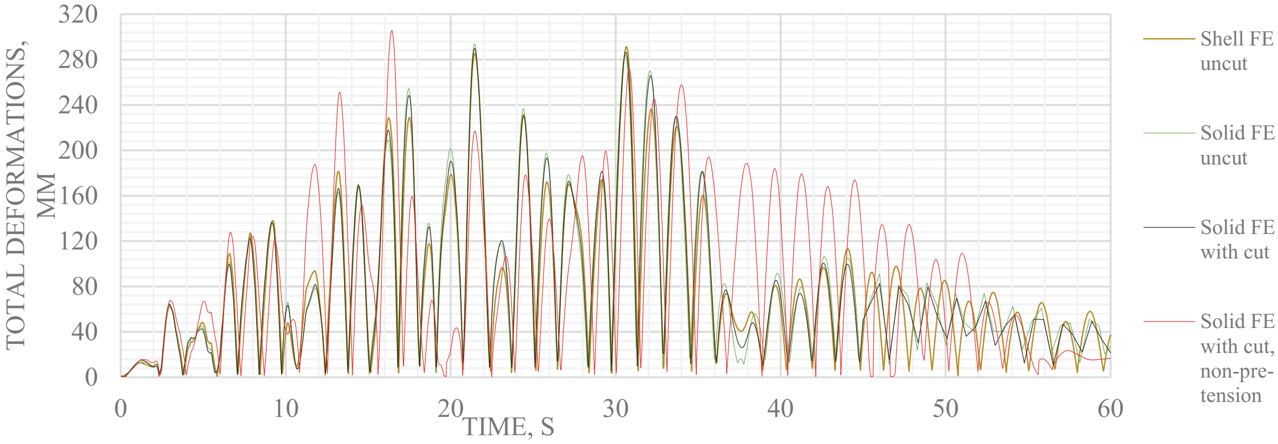

Figure 28. Total deformations multi-story frame in transverse direction with modeling the frame moment connection

The results show that the variants cut and uncut are identical, but without pretension, the frame works differently and its total deformations are higher.

CONCLUSION

It has been found that a butt joint with the outline like a meander is equivalent to a solid column without cutout with 4 plates, compressed with studs a pretention force of 90 kN (fig.1), allowing calculations of entire design model without detailed modeling of the frame moment connection, simply by applying fixed joint of column and beam. Additionally, one advantage of this type of butt joint is its ability to solve the issue of installing diaphragm plates in the box-section column body.

It should be noted that the next stage of the study involves direct testing of the entire frame moment connection on the stand and further consideration of its individual factors and elements to determine their qualitative impact on its bearing capacity, namely the influence of:
1) friction coefficient between steel plates;
2) bolt or studs pretension values;
3) the size of the amplitude and the rounding of the meander;
4) the size of the gaps (tolerances) between the columns to be joined;
5) the vertical distance between the intersecting bolts or studs

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