ДГКС ASES | E-10
Kongres 2026
Congress 2026

doi: 10.67563/ASESCONF2026098Z

Sofia Žugić[1], Milivoje Rogač[2]

HAUNCH EFFECT ON STEEL FRAME ULTIMATE CAPACITY UNDER LATERAL LOADING

Summary: This paper investigates the effect of a haunch on the ultimate capacity and lateral stiffness of a single-bay, two-hinged, unbraced steel frame subjected to gravity loading and a concentrated lateral force. For the frame without haunches, analytical and numerical analyses were carried out using *beam* and *shell* finite elements, whereas the identical frame with haunches was analysed numerically using *shell* elements in the *Abaqus* software package. The dimensions and shape of the haunch were varied within a parametric analysis, considering three characteristic shapes. The results show that the presence of haunches significantly increases the ultimate capacity and stiffness of the system and affects the development of plasticity and the location of plastic hinges. Both parameters influence the frame response, although the haunch dimensions have a more pronounced effect than the haunch shape.

Keywords: steel frame, haunch, lateral force, ultimate capacity

UTICAJ VUTE NA GRANIČNU NOSIVOST ČELIČNOG RAMA IZLOŽENOG BOČNOJ SILI

Rezime: U radu je analiziran uticaj vute na graničnu nosivost i bočnu krutost jednobrodnog, dvozglobnog i neukrućenog čeličnog rama izloženog gravitacionom opterećenju i koncentrisanoj bočnoj sili. Za ram bez vute sprovedene su analitička analiza i numeričke analize primjenom *beam* i *shell* konačnih elemenata, dok je identičan ram sa vutom analiziran numerički primjenom *shell* elemenata u programskom paketu *Abaqus*. Parametarskom analizom varirane su dimenzije i oblik vute, pri čemu su razmatrana tri karakteristična oblika. Rezultati pokazuju da prisustvo vute značajno povećava nosivost i krutost sistema i utiče na razvoj plastifikacije i položaj plastičnih zglobova. Utvrđeno je da oba analizirana parametra utiču na odgovor rama, ali da dimenzije vute imaju izraženiji uticaj od njenog oblika.

Ključne reči: čelični ram, vuta, bočna sila, granična nosivost

[1] University of Montenegro, Faculty of Civil Engineering, Podgorica, Montenegro, zugicsofia22@gmail.com
[2] University of Montenegro, Faculty of Civil Engineering, Podgorica, Montenegro

1. INTRODUCTION

Unbraced steel frame systems are widely used in modern construction due to their ability to span large distances, relatively low self-weight, and adaptability to various architectural and functional requirements. Their structural response largely depends on the behaviour and rotational stiffness of beam-to-column connections, which are most commonly executed as welded or bolted connections in practice.

To increase the stiffness and load-bearing capacity of the system, local strengthening in the form of haunches is often applied in the beam-to-column connection region. The presence of a haunch may contribute to a more favourable distribution of internal forces, a reduction in stress concentrations, and controlled development of plasticity.

This paper analyses the elastoplastic response of a single-bay, two-hinged, unbraced steel frame. The frame is subjected to a uniformly distributed gravity load of constant intensity and a concentrated lateral force whose intensity is increased until collapse. The columns and beam have a constant I-shaped cross-section, while the connections between them are modelled as welded. The analysis was conducted assuming ideal local and global stability of the system.

The numerical analysis was performed using the finite element method in the *Abaqus* software package [1]. For the frame without haunches, *beam* and *shell* models were developed, and their validation was carried out by comparing the results with the analytical solution. The frame with haunches was analysed only numerically using *shell* elements. The effect of the haunch was investigated through a parametric analysis comprising two parameters: the shape and dimensions of the haunch.

The aim of the paper is to analyse the effect of the haunch on the ultimate capacity, lateral stiffness, and collapse mechanism of the frame. The contribution of the paper is reflected in the development of a specific numerical model and a wide variation of haunch shape and dimensions within the parametric study (Section 4.1).

2. REVIEW OF PREVIOUS RESEARCH

The effect of haunches on the behaviour of steel beam-to-column connections has been investigated in numerous numerical and experimental studies [2–7], confirming the relevance and importance of this research topic.

Study [2], which is most closely related to the present study, analysed 21 numerical models developed in the *Abaqus* software package, considering haunch angles of 15°, 30°, and 45° relative to the horizontal plane, together with different stiffener configurations. Reducing the haunch angle increased the connection capacity, although smaller angles promoted plasticity near the connection. Increasing the angle from 15° to 45° reduced the capacity, while local stiffeners significantly improved the connection response. A haunch angle of approximately 30°, combined with appropriate stiffeners, was identified as the most favourable solution.

Studies [3] and [4] showed that increasing the haunch length reduces the bending moment in the beam and stresses in welded joints and improves connection capacity, although it may increase the axial force in the haunch flange and the shear force in the beam web. Studies [5] and [6] further confirmed that haunch geometry, particularly its height and inclination angle, significantly affects moment capacity, initial rotational stiffness, and force transfer.

Study [7] concluded that the use of a haunch contributes to relocating the plastic hinge away from the immediate beam-to-column connection region and enables the development of a more favourable structural response mechanism.

Based on previous research, it may be concluded that haunches generally increase connection strength and stiffness, reduce stress concentrations, and relocate plastic hinges away from the immediate connection region, while their overall effect also depends on the ratio between haunch length and height.

3. FRAME WITHOUT HAUNCHES

This section presents the analysis of a single-bay, two-hinged, unbraced steel frame without haunches, which provides the basis for validating the numerical *beam* and *shell* models and for their subsequent comparison with the response of the frame with haunches. The frame has a span of 8.0 m and column heights of 4.0 m, while the columns and beam have the same welded I-shaped cross-section, with an overall depth of 400 mm, flange width of 250 mm, web thickness of 5 mm, and flange thickness of 10 mm (Figure 1). A linear elastic–perfectly plastic material model was adopted for the steel, also shown in Figure 1. The numerical analysis did not include the effects of geometric nonlinearity. The frame is subjected to a uniformly distributed gravity load of constant intensity of 20 kN/m along the beam and to a concentrated lateral force whose intensity is increased until collapse.

First, the analytical solution of the frame is presented, after which numerical models were developed using *beam* and *shell* finite elements. Finally, the analytical and numerical results were compared by considering the force–displacement curves, ultimate capacity, stress distribution, and development of plasticity.

3.1. ANALYTICAL SOLUTION

The analytical procedure for determining the lateral capacity of the frame was carried out using a *step-by-step method*. Figure 1 shows the analysed frame, together with the defined collapse load (P^*) and the locations of the plastic hinges at the collapse mechanism.

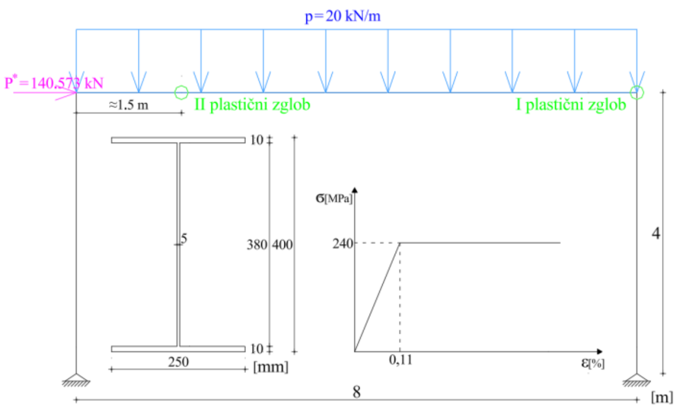

Figure 1: Overall frame geometry, cross-section, steel stress–strain diagram, and locations of plastic hinges at the collapse mechanism (P^* = 140.573 kN)

The first plastic hinge forms in the connection region between the right column and the beam at a force P_1 of 99.235 kN. The second plastic hinge forms in the beam at a distance of approximately 1.5 m from the connection region between the left column and the beam, at a force P_2 of 41.338 kN. The ultimate load of the analysed frame is: $P^* = P_1 + P_2 = 99.235 + 41.338 = 140.573$ kN.

3.2. NUMERICAL SOLUTION – *BEAM* – FE

The *beam* finite element model was developed as a single two-dimensional assembly. The adopted I-shaped cross-section was assigned to the elements, and its orientation was defined. The analysis was carried out using a nonlinear static procedure. In the initial step, the pinned supports of the frame were defined. A uniformly distributed gravity load of 20 kN/m was then applied to the beam, followed in the final step by a concentrated lateral force at the joint between the left column and the beam. The lateral force was applied incrementally until collapse, while the applied concentrated force and the corresponding lateral displacement at the same joint were monitored.

The model was discretised using B22 finite elements. A convergence study established an optimal finite element size of 50 mm.

The results of the numerical analysis of the *beam* model are presented in Section 3.4.

3.3. NUMERICAL SOLUTION – *SHELL* – FE

The *shell* finite element model was developed as a three-dimensional model, with the columns and beam modelled as separate surface elements. The corresponding thicknesses were assigned to the webs and flanges. The columns and beam were rigidly connected in the *Assembly* module. As in the *beam* model, a nonlinear static analysis was performed. A uniformly distributed gravity load of 20 kN/m was applied to the top flange of the beam as a surface pressure of 80 kN/m². Reference points coupled kinematically to the corresponding end cross-sections were used to define the support conditions and apply the lateral force. The concentrated lateral force was applied incrementally until collapse through the reference point located in the connection region between the left column and the beam. The applied lateral force and the corresponding lateral displacement were monitored at this point. The model was discretised using S4R finite elements. A convergence study established an optimal finite element size of 50 mm.

The results of the numerical analysis of the *shell* model are presented in Section 3.4.

3.4. ANALYSIS OF RESULTS

Figure 2 presents the force–displacement curves obtained from the analytical calculation and the numerical models using *beam* and *shell* finite elements.

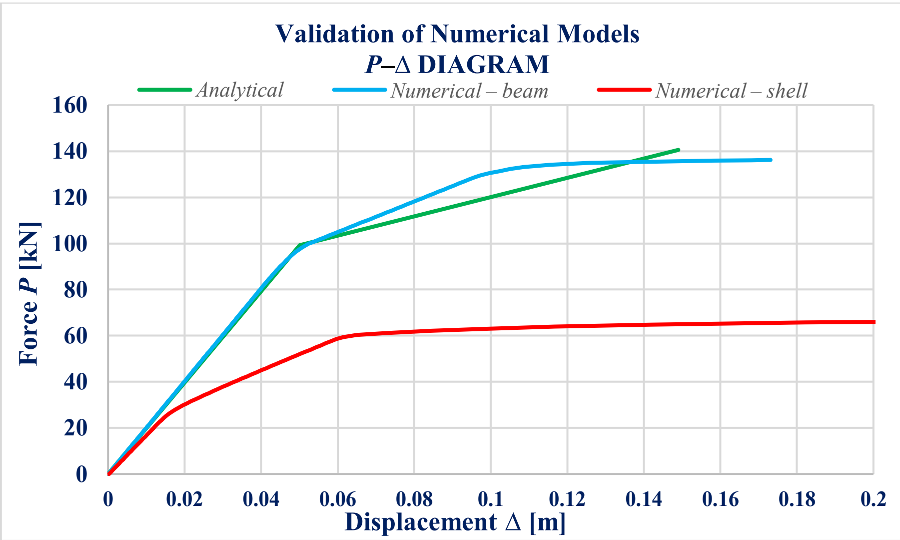

Figure 2: Force–displacement diagram – validation of the numerical models

The analytical solution and the *beam* model show very good agreement in terms of initial stiffness, ultimate capacity, and collapse mechanism (Figure 2). The locations of the plastic hinges obtained from the analytical calculation are shown in Figure 1, while in the *beam* model the plastic hinges form at the same locations. The collapse mechanism of the *beam* model develops at a lateral force of 136.24 kN, which is in good agreement with the analytically determined ultimate load.

The force–displacement curve of the numerical *shell* model (Figure 2) shows significant deviations from the analytical solution and the *beam* model, reflected in substantially lower stiffness and capacity. Unlike the previous two models, the *shell* model enables detailed monitoring of the development of the local stress–strain state, as shown in Figure 3.

Initial yielding occurs in the web of the connection between the right column and the beam at a lateral force of approximately 22.5 kN (Figure 3 – left). With a further increase in loading, the plastic zone spreads through the web, leading to a reduction in the global stiffness of the system and the first significant change in slope on the force–displacement curve at a force of 27.9 kN (Figure 2 – red *P–Δ* curve; Figure 3 – centre). As plasticity continues to develop through the connection region, local rotation occurs and the first plastic hinge forms at a force of approximately 57.6 kN (Figure 3 – right). Thereafter, plasticity also spreads to the connection region between the left column and the beam, where the second plastic hinge forms, and the collapse mechanism develops at a lateral force of 64.8 kN.

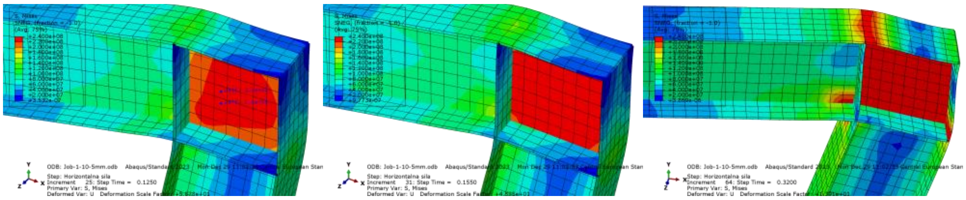

Figure 3: Distribution of von Mises stresses in the connection between the right column and the beam – initial yielding at P_y = 22.5 kN, spreading of the plastic zone at P_1 = 27.9 kN, and formation of the first plastic hinge at P_2 = 57.6 kN

The difference between the *beam* and *shell* models primarily results from the different treatment of the beam-to-column connection. The *beam* model idealises the connection as fully rigid and does not allow a detailed assessment of its local deformability and stress state. In addition, although the *beam* formulation accounts for the effect of shear on element deformations, shear stresses are not included in the calculation of the equivalent stress used as the yielding criterion. By contrast, the *shell* model accounts for local shear stresses, a more realistic rotational stiffness of the connection, and the gradual development of plasticity. Consequently, the yielding criterion is reached earlier, resulting in significantly lower stiffness and ultimate capacity than in the *beam* model.

The obtained results show that the *shell* model provides a more detailed simulation of the local stress–strain behaviour of the beam-to-column connection. Although it gives lower values of stiffness and ultimate capacity, as well as a different location of the second plastic hinge compared with the analytical solution and the *beam* model, the sequence of deformation, development of plasticity, and formation of the collapse mechanism confirms the justification for its application. Based on the comparison performed, the *beam* and *shell* models were validated.

4. FRAME WITH HAUNCHES

The frame with haunches was modelled using *shell* finite elements, based on the previously validated *shell* model of the frame without haunches. The haunches were placed in the beam-to-column connection regions and connected to the webs and flanges of the primary members so as to form an integral assembly. The web and flange thicknesses of the haunch were kept constant in all analysed models, with a web thickness of 5 mm and a flange thickness of 10 mm. Local stiffeners were provided at the ends of the haunches. The thickness of all local stiffeners, including both those at the haunch ends and those in the beam-to-column connection region, was set to 5 mm (Figure 4).

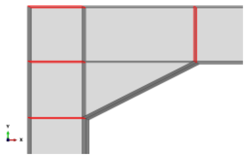

Figure 4: Location of the modelled stiffeners

The remaining geometric and material properties of the frame, support conditions, loading procedure, and type of analysis were kept the same as in the *shell* model of the frame without haunches. This enabled a direct assessment of the effect of the haunch on the ultimate capacity, lateral stiffness, development of plasticity, and collapse mechanism of the system.

4.1. PARAMETRIC ANALYSIS

The parametric analysis was conducted to investigate the effects of haunch dimensions and shape on the elastoplastic response of the frame. The haunch dimensions were defined by the parameters l and h, where l denotes the haunch length measured along the beam and h denotes the haunch web depth measured along the column. The haunch shape was defined by the ratio l:h, and three characteristic shapes were considered: Shape 1 with l:h = 2:1, Shape 2 with l:h = 1:2, and Shape 3 with l:h = 1:1. The analysed configurations, including their dimensions, l:h ratios, and haunch inclination angles θ relative to the horizontal, are presented in Table 1.

Table 1: Analysed haunch configurations

Shape	l:h	θ [°]	Analysed dimensions $l \times h$ [mm]
1	2:1	26.6	200×100, 400×200, 600×300, 800×400, 1200×600, 1600×800
2	1:2	63.4	100×200, 200×400, 300×600, 400×800, 600×1200, 800×1600
3	1:1	45.0	100×100, 200×200, 300×300, 400×400, 600×600, 800×800, 1200×1200, 1600×1600

For each configuration, the force–displacement response, ultimate capacity, lateral stiffness, plasticity development, and plastic-hinge locations were evaluated. Very small haunch dimensions, such as 100 × 100 mm, and very large dimensions, such as 1600 × 1600 mm, are not commonly used in engineering practice and were analysed solely from a theoretical standpoint.

4.2. ANALYSIS AND DISCUSSION OF RESULTS

Figures 5–7 show the force–displacement curves for Haunch Shapes 1–3. The response of the reference *beam* model is shown by a dashed line, while the remaining curves correspond to the shell model of the frame without haunches and the shell models of frames with haunches.

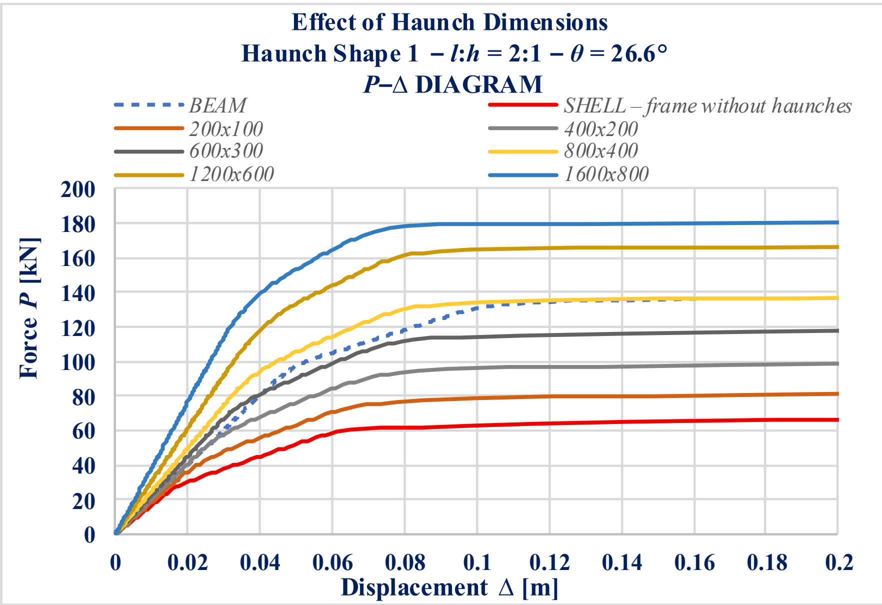

Figure 5: Force–displacement curve – effect of haunch dimensions – Haunch Shape 1

For Haunch Shape 1 (Figure 5), with an *l:h* ratio of 2:1, increasing the haunch dimensions leads to a continuous increase in the lateral stiffness and ultimate capacity of the frame. Compared with the *shell* model of the frame without haunches, the models with haunch dimensions of 200 × 100 mm, 400 × 200 mm, and 600 × 300 mm achieve increases in ultimate capacity of approximately 23.6 %, 51.4 %, and 79.2 %, respectively. However, their effect is still not sufficiently pronounced for the system response to approach that of the idealised *beam* model.

The model with haunch dimensions of 800 × 400 mm achieves an increase in ultimate capacity of approximately 109.7 % and provides the response closest to that of the *beam* model, which assumes a fully rigid beam-to-column connection. The obtained collapse load of 135.9 kN is only approximately 0.25 % lower than the value obtained using the *beam* model, which is 136.24 kN. These dimensions are also consistent with the recommendations for the design of portal frames given in reference [8], according to which the haunch length is approximately 10 % of the frame span, while its depth approximately corresponds to the beam depth.

With a further increase in the haunch dimensions to 1200 × 600 mm and 1600 × 800 mm, the ultimate capacity increases further by approximately 156.9 % and 179.3 %, respectively. However, this is accompanied by a significant increase in system stiffness, causing the response of these models to deviate from that of the *beam* model.

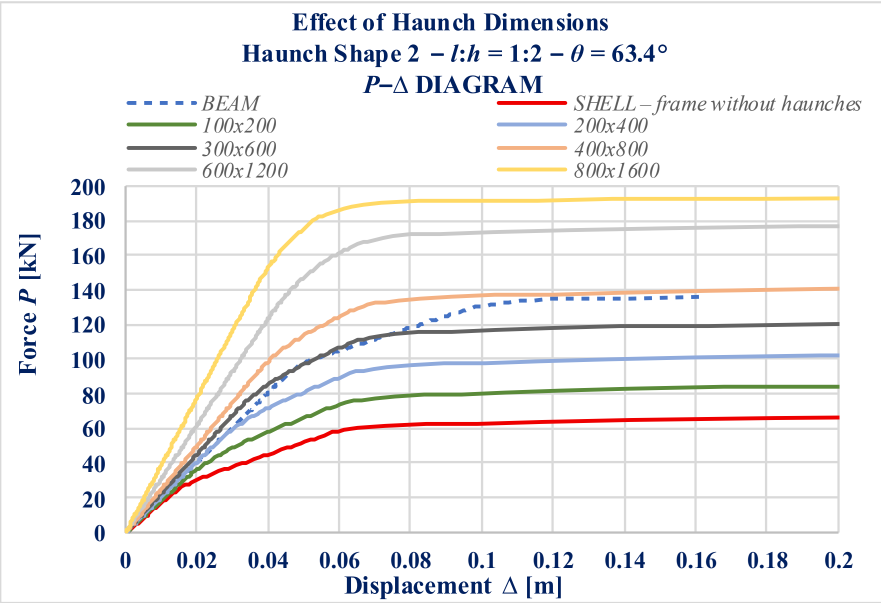

Figure 6: Force–displacement curve – effect of haunch dimensions – Haunch Shape 2

For Haunch Shape 2 (Figure 6), with an *l:h* ratio of 1:2, a continuous increase in the ultimate capacity and lateral stiffness of the system can also be observed as the haunch dimensions increase. The models with dimensions of 100 × 200 mm, 200 × 400 mm, and 300 × 600 mm achieve increases in ultimate capacity of approximately 27.8 %, 55.6 %, and 84.7 %, respectively, compared with the *shell* model of the frame without haunches.

The model with haunch dimensions of 400 × 800 mm achieves an increase in ultimate capacity of approximately 115.3 % and provides the response closest to that of the *beam* model, while also exhibiting the most favourable balance between capacity, stiffness, and deformability within this haunch shape. The obtained collapse load of 139.5 kN is approximately 2.4 % higher than the value obtained using the *beam* model.

With a further increase in the haunch dimensions to 600 × 1200 mm and 800 × 1600 mm, the ultimate capacity continues to increase, reaching approximately 171.6 % and 197.7 %, respectively. However, as in the case of Haunch Shape 1, this increase in capacity is accompanied by a significant increase in the lateral stiffness of the system, causing the response of these models to progressively deviate from that of the *beam* model.

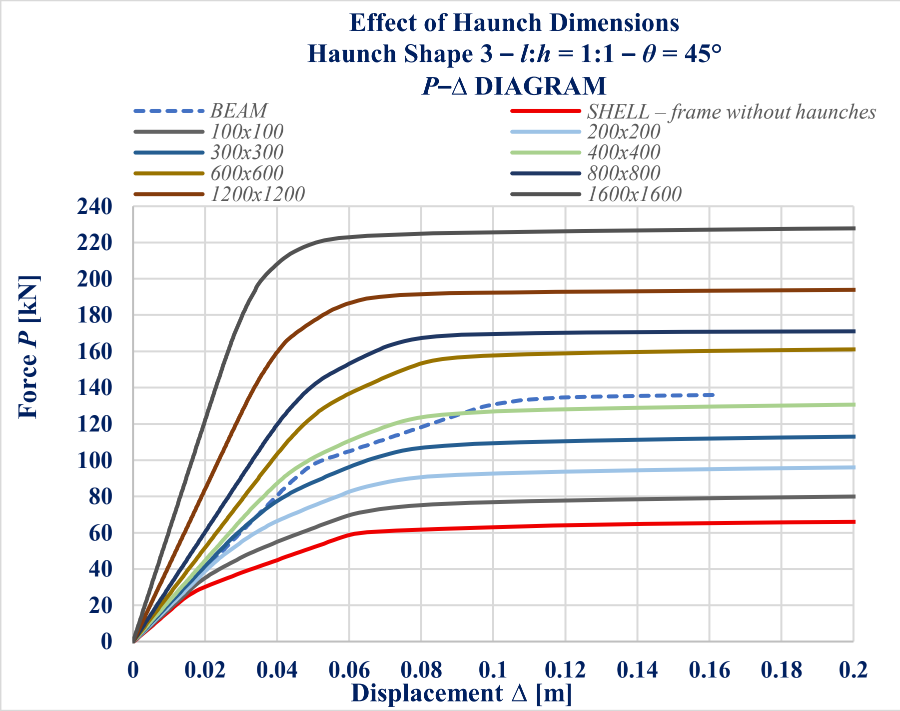

Figure 7: Force–displacement curve – effect of haunch dimensions – Haunch Shape 3

For Haunch Shape 3, with an *l:h* ratio of 1:1, increasing the haunch dimensions also leads to an increase in the ultimate capacity and lateral stiffness of the system. The models with dimensions of 100 × 100 mm, 200 × 200 mm, and 300 × 300 mm achieve increases in ultimate capacity of approximately 22.2 %, 45.8 %, and 72.2 %, respectively, compared with the *shell* model of the frame without haunches. The model with haunch dimensions of 400 × 400 mm achieves an increase in ultimate capacity of approximately 100.0 % and, within this haunch shape, provides the response closest to that of the *beam* model. The obtained collapse load of 129.6 kN is approximately 4.9 % lower than the value obtained using the *beam* model. With a further increase in the dimensions to 600 × 600 mm, 800 × 800 mm, 1200 × 1200 mm, and 1600 × 1600 mm, the ultimate capacity continues to increase, reaching approximately 147.2 %, 161.1 %, 198.4 %, and 251.1 %, respectively. However, as with the previous two haunch shapes, the response of these models progressively deviates from that of the *beam* model.

The obtained results show that increasing the haunch dimensions for all three shapes leads to an increase in the lateral stiffness and ultimate capacity of the system, as well as to a gradual relocation of the plastic hinge formation points away from the immediate beam-to-column connection region, which is consistent with the results reported in studies [2–7]. For all three haunch shapes, the relative increase in ultimate capacity gradually decreases as the dimensions increase, indicating that the effect of further increasing the haunch dimensions becomes progressively less pronounced. This trend is observed up to the dimensions identified as the most favourable for each haunch shape. Models with extremely large haunch dimensions constitute an exception to this trend.

A comparison of the haunch shapes shows that Shape 2 achieves the highest ultimate capacity in all analysed groups of dimensions, followed by Shape 1, while Shape 3 gives the lowest values. The results indicate that increasing the haunch height has a greater effect on ultimate capacity than increasing its length, with the differences between the individual shapes becoming more pronounced as the dimensions increase.

In addition to its effect on capacity and stiffness, the haunch shape significantly influences the development of plasticity and the location of plastic hinges. In Shape 1, plasticity is predominantly directed towards the column; in Shape 2, towards the beam; while in Shape 3, it develops approximately symmetrically towards both members.

Figure 8 presents three models which, within the analysis of the effect of haunch dimensions, provided the response closest to that of the reference *beam* model for each of the considered haunch shapes.

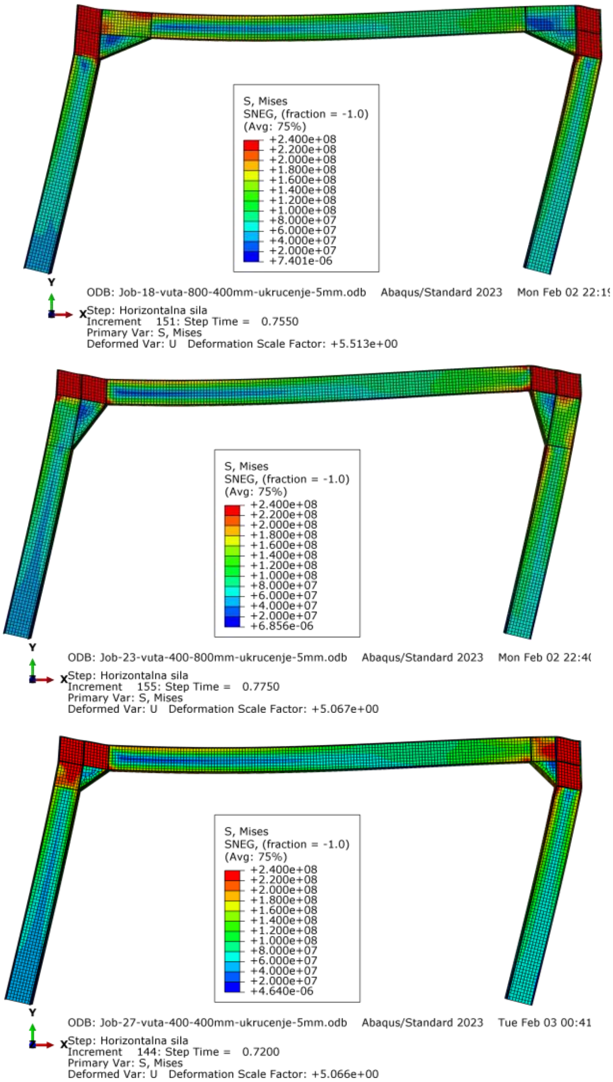

Figure 8: Distribution of von Mises stresses at the formation of the collapse mechanism for the 800 × 400 mm model (P^* = 135.9 kN), the 400 × 800 mm model (P^* = 139.5 kN), and the 400 × 400 mm model (P^* = 129.6 kN)

Although the model with haunch dimensions of 800 × 400 mm provides the response closest to that of the reference *beam* model in terms of ultimate capacity and lateral stiffness, the 400 × 800 mm model exhibits the most favourable behaviour from the strong-column–weak-beam design perspective, since the plastic hinges form in the beam, outside the immediate beam-to-column connection region.

5. CONCLUSIONS

Based on the analyses conducted for the specific frame geometry with and without haunches, the following conclusions can be drawn. Comparison of the analytical solution and the beam model of the frame without haunches showed very good agreement in terms of capacity, stiffness, and collapse mechanism, whereas the shell model yielded significantly lower values. This discrepancy arises because the beam model idealises the beam-to-column connection as fully rigid, while shear stresses, although they influence the deformations, are not included in the calculation of the equivalent stress used as the yielding criterion. The shell model accounts for local shear stresses and connection deformability; therefore, yielding and the development of plasticity occur earlier, resulting in lower stiffness and ultimate capacity.

The analysis of the haunch dimensions and shape showed that increasing the haunch dimensions leads to an increase in the ultimate capacity and lateral stiffness of the system, as well as to a gradual relocation of the plastic hinge formation points away from the immediate beam-to-column connection region. Shape 2 provides the highest ultimate capacity, followed by Shape 1, while Shape 3 gives the lowest values. The haunch shape also affects the direction of plasticity development: increasing the haunch height directs plasticity towards the beam, whereas increasing its length predominantly directs plasticity towards the column. The obtained results support the common design assumption of a fully rigid connection in *beam* models, provided that the haunch is properly proportioned so that the actual connection response closely approaches such idealised behaviour.

The 800 × 400 mm model most accurately reproduces the capacity and stiffness of the *beam* model, whereas the 400 × 800 mm model provides a structurally more favourable response: the plastic hinges form in the beam, outside the beam-to-column connection region, in accordance with the strong-column–weak-beam principle.

REFERENCES

[1] Dassault Systèmes. Abaqus Analysis User’s Guide, Dassault Systèmes Simulia Corp., 2017.

[2] Sadid M. S, Yaman Z, Nasery M. Effect of the haunch angle and stiffener types on column-beam connection behaviour under static loading, Civil Engineering Beyond Limits, 3, 2022, 1-13.

[3] Liu Y. J, Wang Y. The study on mechanical property for welded haunch-reinforced seismic connections of steel frame, Applied Mechanics and Materials, 501-504, 2014, 485-494.

[4] Baharmast A. Evaluation of column-tree moment resisting connection with end plates and haunched beam (Research Note), International Journal of Engineering, 28 (12), 2015, 1702-1710.

[5] Zhao H, Shi G, Chen X, Xiao T. Numerical simulation and mechanical model of steel beam-to-column joints retrofitted by haunches, Journal of Constructional Steel Research, 185, 2021, 106858.

[6] Zhao H, Shi G, Chen X, Xiao T. Finite element analysis and design of retrofitted beam-to-column joints with welded haunches, Journal of Constructional Steel Research, 186, 2021, 106924.

[7] Ajay K. S, Vesmawala Gaurang R. Modern strengthening strategies for steel moment resisting frames: State-of-the-art review, Civil and Environmental Research, 3, 2013, 137-144.

[8] Institution of Structural Engineers. Manual for the Design of Steelwork Building Structures to Eurocode 3, Institution of Structural Engineers, London, 2010.