

Finite Element Analysis of Flexible Roll Forming of Height Variable Profiles Made of Advanced High Strength DP980 Steel

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Abstract. In the present study, the technical feasibility of manufacturing a height-variable profile from an advanced high-strength steel (AHSS) sheet using the roll forming process was investigated through finite element analysis (FEA). The study focused on the production of a cross member used in a B-segment passenger vehicle. For this purpose, the kinematics of the forming rolls in both the height and longitudinal directions were derived and integrated into the finite element model. The sheet metal was modeled using both shell and solid (3D) elements. These two different modeling strategies were evaluated in terms of the formed profile geometry. The results demonstrated that the manufacturing of the selected cross member is feasible with the derived roll kinematics. Additionally, it was observed that the use of shell elements led to higher deviations from the desired geometry compared to solid elements. The analyses are planned to be validated experimentally in the next phase of the study.

Introduction

In the automotive industry, two major trends that have defined the past decade are vehicle lightweighting efforts aimed at reducing exhaust emissions and initiatives to lower production costs. The roll forming process is particularly suitable for the economical manufacturing of profile-shaped components made from high-strength steel sheets. However, this method inherently produces profiles with a constant cross-section [1]. Nevertheless, in automotive applications, the use of straight profiles is often inefficient in terms of load-bearing capacity. Therefore, it becomes necessary to produce profiles with variable height along their length.

In recent years, flexible roll forming (FRF) has emerged as a promising manufacturing technique to overcome this limitation by enabling the production of profiles with a variable cross-section along their length. In contrast to conventional roll forming, FRF allows the roll stands to move laterally, enabling the gradual variation of profile height and thus improving structural efficiency and load-bearing performance. Owing to these advantages, flexible roll forming has attracted increasing attention, particularly for lightweight structural applications in the automotive industry [2-5].

However, the majority of previous studies on flexible roll forming have focused on low- to medium-strength steels, primarily due to their higher formability and lower risk of process instabilities. The application of FRF to advanced high-strength steels (AHSS), such as DP980, remains limited in the literature. This is mainly attributed to the increased forming forces, higher springback, and elevated risk of edge cracking associated with these materials. As a result, the forming behavior and geometrical accuracy of height-variable profiles made from AHSS are not yet sufficiently understood.

In this study, a finite element analysis of the flexible roll forming process applied to height-variable profiles made of DP980 advanced high-strength steel is presented. The numerical model aims to capture the deformation behavior, and final geometry of the formed profiles. Particular emphasis is

placed on evaluating the capability of different element formulations, namely solid and shell elements, to accurately predict the profile geometry and deformation characteristics.

Material and Methodology

The finite element model of the height-variable profile was developed using MSC.Marc 2022.4. A schematic side view of the investigated profile geometry is shown in Fig. 1. The profile has a total length of 900 mm and corresponds to a hat-shaped cross-section, which is commonly used in automotive structural applications. The maximum profile height is 21 mm, while the minimum height is 13 mm. Between these two regions, the profile geometry transitions through three different radii, whereas the remaining sections are designed with linear height variation. The sheet thickness of the profile is constant and equal to 1.0 mm.

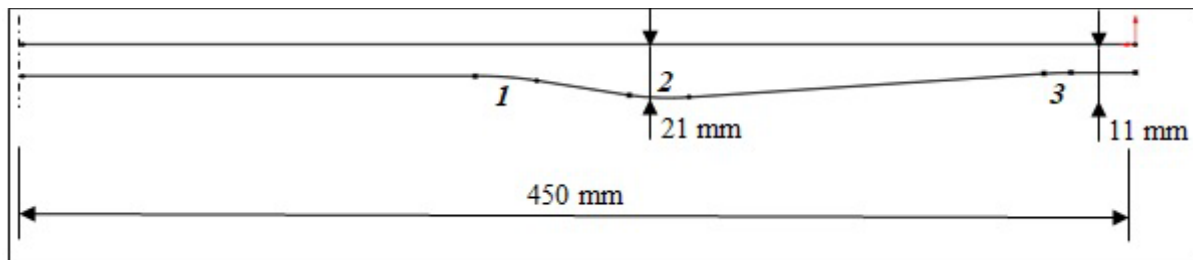


Fig. 1. Geometrical properties of the investigated profile.

The roll geometries were modeled as rigid bodies. The arrangement and dimensions of the forming, support, and feeding rolls are schematically illustrated in Fig. 2. The feeding rolls, highlighted in yellow and orange, rotate only about their own axes and do not perform any additional translational motion during the process. The support rolls, shown in green, also rotate during forming; however, their positions in the X-direction are adjusted at each forming step to match the local profile geometry.

The forming rolls, depicted in blue, perform both rotational and translational motions during the forming process. The lower forming roll is designed to be movable only in the height direction (Y-direction), whereas the upper forming roll is movable in both the Y- and Z-directions. This kinematic configuration enables the gradual variation of profile height along the longitudinal direction and represents the key mechanism of the flexible roll forming process.

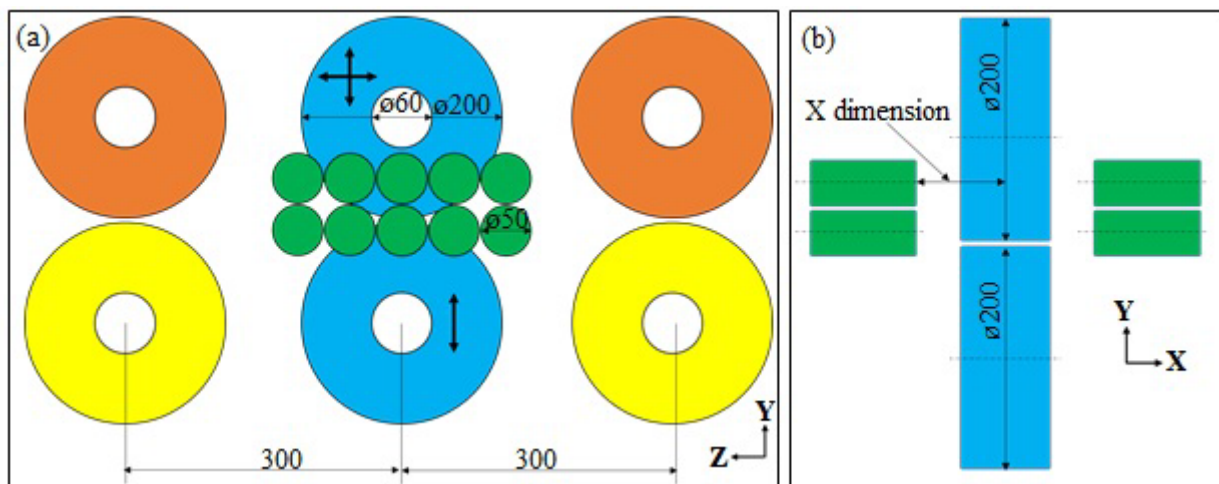


Fig. 2. Schematic view of the roll configuration (a) side view and (b) front view of forming rolls.

The motions of the top and bottom forming rolls in the Y- and Z-directions were defined based on the target profile geometry shown in Fig. 1. The roll trajectories at the final forming step are presented as representative examples in Fig. 3 and Fig. 4. During the derivation of these kinematics, particular attention was given to ensuring that the forming rolls accurately follow the cross-section of the height-

variable profile and remain in continuous tangential contact with the sheet throughout the forming process.

The investigated hat-shaped profile was designed to be bent by 10 degrees at each forming step, resulting in a total of nine forming steps to achieve the final geometry. This stepwise forming strategy enables a gradual deformation of the sheet and reduces the risk of excessive local strains, which is particularly important when forming advanced high-strength steels such as DP980.

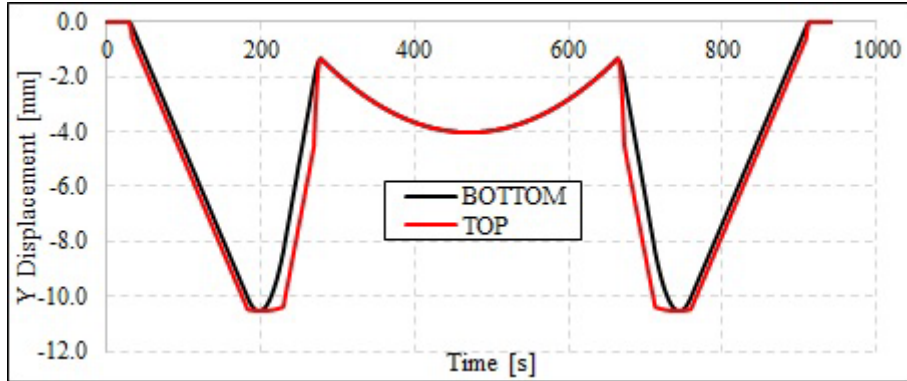


Fig. 3. Displacement in Y-direction of the top and bottom forming rolls in the last forming station.

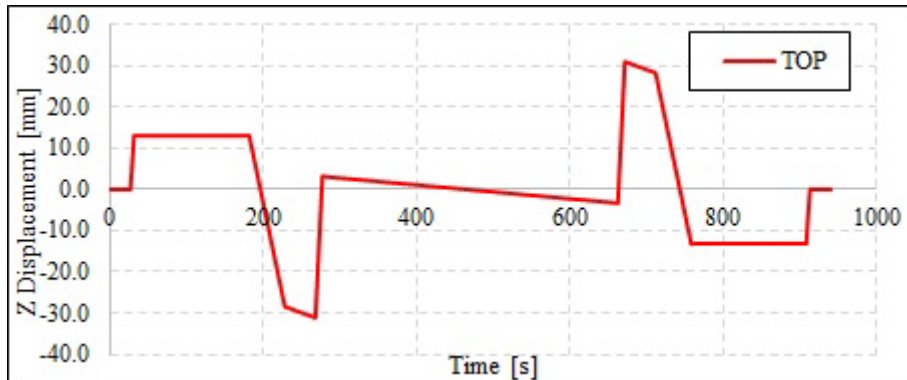


Fig. 4. Displacement in Z-direction of the top forming roll in the last forming station.

In the developed finite element model, the sheet material was defined as deformable, while the rolls were modeled as rigid bodies. An example of the numerical model is shown in Fig. 6. Owing to the symmetric geometry of the hat-shaped profile, only half of the sheet was modeled to reduce computational cost. The sheet was constrained by applying displacement boundary conditions in the directions indicated by the green arrows in Fig. 5. In addition, the sheet motion was restricted in the direction shown by the black arrows. The rigid rolls were driven over the sheet according to the prescribed kinematics described in the previous section.

To investigate the influence of element type on the prediction of the profile geometry, two different finite element models were established. In the first model, three-dimensional solid elements (7-type, linear integrated) were employed. In the second model, two-dimensional shell elements with three integration points in thickness direction (139-type, linear integrated) were used. For both employed element types, a fully integrated formulation was selected. In addition, an assumed strain formulation together with constant dilatation was activated to control hourglass effects.

Both models consisted of 9,000 elements, ensuring a direct comparison between the two modeling approaches. Both models have a single element over thickness. However, in order to have same integration points on the surface of the sheet metal, shell model had three integration points over the thickness. A refined mesh was applied in the regions where forming takes place, while coarser elements were used in the less deformed zones to maintain computational efficiency. The width of the elements in bending regions was 0.8 mm. On the flat sections of the profile, an element width of 2.8 mm was selected. Element size in length direction was constant and was equal to 4 mm in all regions.

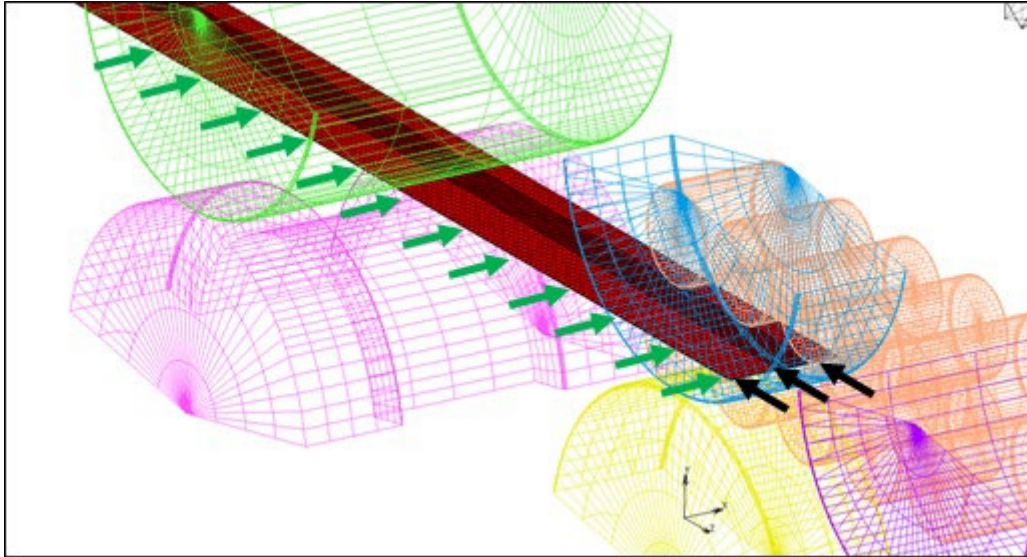


Fig. 5. Finite element model of the flexible roll forming process (green arrows indicate fixed boundary condition in X-direction, black arrows indicate fixed boundary condition in Z-direction).

The mechanical behavior of the DP980 steel used in the finite element analysis was determined using tensile tests in three directions, namely 0° , 45° , and 90° . The tensile test results in the 0° direction and the corresponding material model predictions are exemplarily shown in Fig. 6. During the development of the material model, the constitutive equation given in the figure was employed up to a true plastic strain of 0.20. For true plastic strain values exceeding 0.20, the mechanical strength of the material was assumed to remain constant at 1230 MPa. In addition, the Young's modulus and Poisson's ratio of the DP980 steel were assumed to be 203 GPa and 0.3, respectively. Furthermore, the anisotropy coefficients of the material measured in the 0° , 45° , and 90° directions were 1.02, 0.91, and 1.22, respectively. All these parameters were used to describe the material behavior using the Hill anisotropic material model.

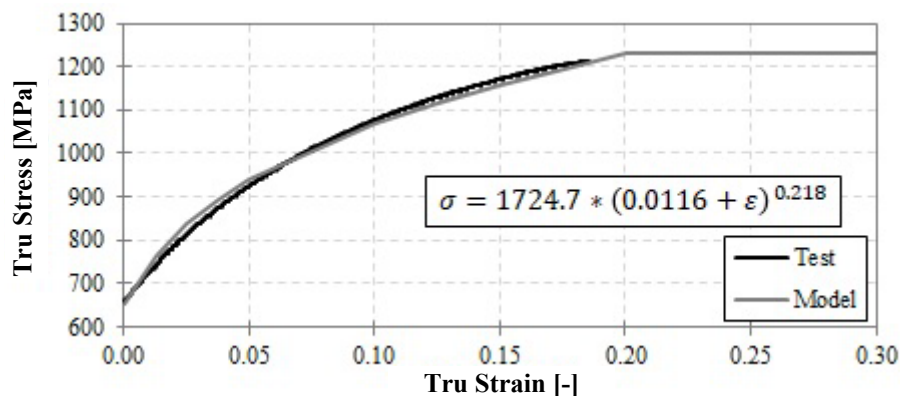


Fig. 6. Tensile test results and corresponding material model of the DP980 steel.

In the roll-forming process, sheet materials are bent progressively through successive forming stages. Consequently, the material becomes unloaded between individual forming stations, which may lead to springback. This behavior may give the impression that regions of the material initially subjected to tensile loading during forming are subsequently deformed under compressive loading. However, for the roll-forming process, all deformation occurring during springback remains within the elastic regime. Therefore, the Bauschinger effect is not considered to be significant under these conditions. Accordingly, kinematic hardening effects are typically neglected in relevant studies reported in the literature [6–11]

In metal forming processes, friction generally plays a significant role. However, during the roll-forming process, rolling contact predominantly occurs between the sheet material and the rolls, and

it is commonly assumed that no significant relative sliding takes place at the sheet–roll interface. This aspect has been specifically investigated in previous studies. The reported results indicate that, for the roll-forming process, friction does not have a pronounced influence on the forming behavior [12, 13]. Accordingly, friction effects have generally been neglected in earlier studies [6-11]. In line with this approach, friction between the sheet and the rolls is also neglected in the present study.

Results and Discussion

The results of the finite element analyses focused primarily on the final profile geometry. The displacement of the profile edge in the X- and Y-directions is presented in Fig. 7, where the X-axis represents the total length of the profile. As shown in Fig. 7(a), a larger displacement in the X-direction is expected in the regions where the profile depth reaches 21 mm compared to the shallower sections. In contrast, in the regions with a depth of 13 mm, the profile edge is expected to exhibit a total displacement of approximately 6 mm in the X-direction due to the imposed geometry variation.

The initial evaluation of the simulation results indicates that the solid element model predicts X-direction displacements closer to the expected 6 mm value. Moreover, in the deeper regions of the profile, the movement of the profile edge in the X-direction remains more restricted, which is consistent with the higher bending stiffness associated with increased profile depth.

As illustrated in Fig. 7(b), the use of solid elements also results in significantly lower fluctuations of the profile edge in the Y-direction compared to the shell element model. This behavior can be attributed to the higher stiffness inherent to the solid element formulation, which suppresses local oscillations and stabilizes the deformation during forming. Consequently, the solid element approach provides a more stable prediction of the height-variable profile in flexible roll forming simulations.

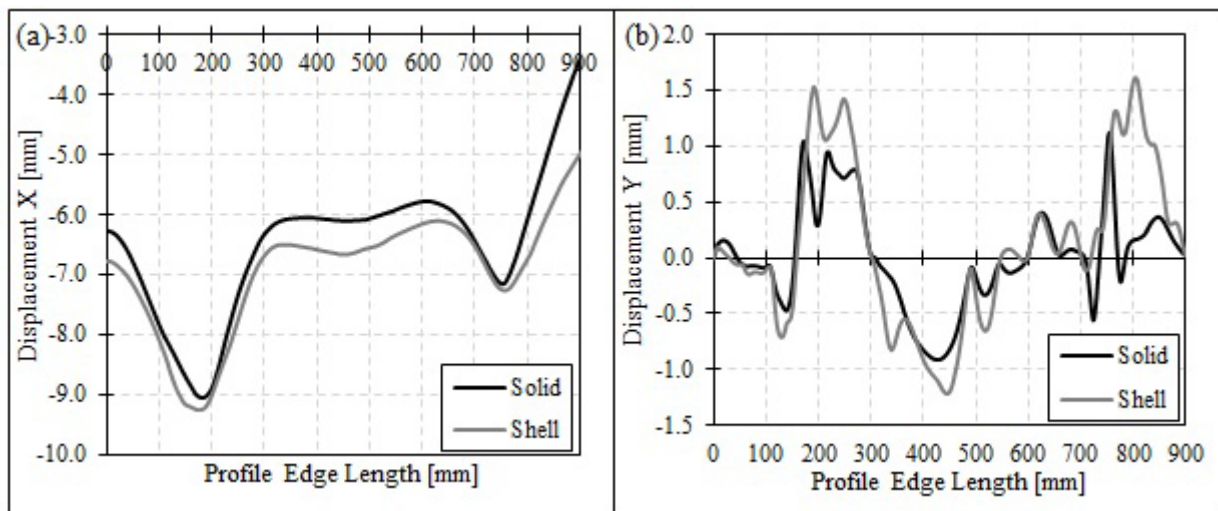


Fig. 7. Displacement in (a) X-direction and (b) Y-direction of the profile edge in finite element models generated with solid and shell elements.

In addition to the displacement of the profile edge, the cross-section of the profile after the final forming step was also examined. The profile cross-sections obtained using shell elements are shown in Fig. 8(a) and (c), whereas the geometries predicted by the solid element model are presented in Fig. 8(b) and (d). The cross-sections extracted at a distance of 200 mm from the profile start correspond to the region with the maximum profile depth.

When shell elements are used, excessive bending is predicted in the central region of the hat profile compared to the expected geometry. Furthermore, as illustrated in Fig. 8(a), pronounced local bending is observed near the profile edge, indicating an overestimation of local deformation. In contrast, the use of solid elements results in a more regular and stable profile geometry after the forming steps. The solid element formulation therefore provides a more reliable representation of the final cross-section for height-variable profiles produced by flexible roll forming.

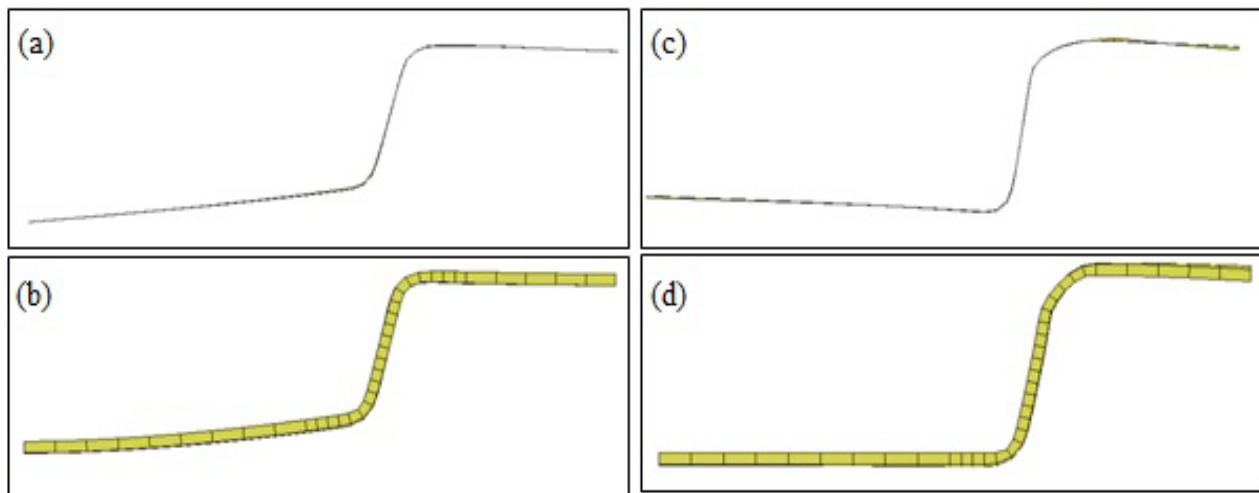


Fig. 8. Profile geometries after forming (a) 100 mm away from the end of shell model, (b) 100 mm away from the end of solid model, (c) 200 mm away from the end of shell model, and (d) 200 mm away from the end of solid model.

One of the important limitations of metal forming processes is the formation of cracks, particularly in edge regions, which is closely related to the limited ductility of the materials. Such cracks generally occur when the material reaches its deformation limits under plastic forming conditions. However, one of the key design principles of the roll-forming process is to avoid plastic deformation in the region commonly referred to as the strip edge during forming. If plastic deformation occurs in these regions, roll-forming-specific geometric defects, such as edge waviness or twist, may develop. For this reason, in the present study, a low bending-angle design was adopted to prevent the occurrence of plastic deformation in the edge region of the formed profile. As a result, no plastic deformation was observed at the profile edges during the forming process in either the shell- or solid-element-based models. Accordingly, it was concluded that there is no risk of crack formation in the process.

Both simulations were performed on the same computer using a single CPU core. The system was equipped with a 20-core processor operating at 5.6 GHz and 64 GB of RAM. The model constructed with solid elements required 5.2 hours to complete. In contrast, the model based on shell elements was completed in 5.6 hours. Although shell elements are generally known to be more computationally efficient than solid elements, three integration points were defined through the thickness direction of the shell elements in order to ensure the presence of integration points on the sheet surface, similar to the solid element formulation. As a result, the computational time of the shell element model was marginally higher.

In the present study, the use of solid elements was found to be more advantageous compared to shell elements. Although shell elements are generally known to be more computationally efficient than solid elements, their stiffness is lower than that of solid elements. As a consequence, the simulation results obtained using shell elements exhibited larger deviations from the expected profile geometry when compared to the solid element model. Furthermore, due to the use of three integration points through the thickness direction in the shell element formulation, the computational time of the shell element model was higher than that of the model based on solid elements.

Summary

In this study, a finite element analysis of the flexible roll forming process for height-variable hat-shaped profiles made of DP980 advanced high-strength steel was presented. A three-dimensional numerical model was developed using MSC.Marc to simulate the forming of a 900 mm long profile with variable depth along its length. The forming kinematics of the top and bottom rolls were derived directly from the target geometry, ensuring continuous tangential contact between the rolls and the sheet throughout the process.

Two different modeling strategies were investigated to evaluate their capability to predict the final profile geometry: a shell element model and a solid element model with identical mesh density. The simulation results showed that the solid element formulation provides more stable predictions of the profile edge displacement and final cross-section geometry. In particular, solid elements were found to better capture the expected X-direction displacement of the profile edge and significantly reduce unwanted fluctuations in the Y-direction. Furthermore, the cross-sectional analysis revealed that shell elements tend to overestimate local bending, especially near the profile edges and in regions with maximum profile depth.

The results clearly demonstrate that element formulation plays a critical role in the numerical simulation of flexible roll forming, especially when advanced high-strength steels are used. Solid elements provide superior geometric accuracy and stability for height-variable profiles.

However, the outcomes of the present study need to be validated through experimental investigations. For this purpose, a roll-forming machine capable of manufacturing height-variable profiles is currently in the design phase. Using this machine, the geometry of the profile at the central region will be measured after each forming step by means of a coordinate measuring machine (CMM). In addition, the deformation of the profile edges in the X-direction will be measured as a function of the forming angle and compared with the simulation results. Although no pronounced edge waviness was observed in the simulation results, this observation also requires experimental validation.

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