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INVESTIGATION OF THE CLINCHING PROCESS UNDER VARIABLE FORMING SPEEDS USING FINITE ELEMENT MODELLING AND POST-JOINT EXTRACTION ANALYSIS

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ABSTRACT

This study investigates the clinching joining process at different forming speeds using Finite Element Method (FEM) simulations. The objective is to analyze how process velocity influences material flow, stress distribution, deformation behavior, and final joint geometry. A numerical model was developed to replicate the clinching process, enabling the extraction of relevant mechanical characteristics such as local strain accumulation, contact pressure profiles, and residual stress fields in the joint region. The resulting clinched connections were further subjected to a simulated pull-out test to evaluate joint strength and separation behavior. Force–displacement curves were generated to quantify the extraction forces under different joining conditions, with particular attention to peak force levels and the onset of structural failure mechanisms. The data obtained provide insight into the correlation between forming speed and structural integrity of clinched joints. The outcomes of the research contribute to a deeper understanding of process parameters governing clinching, facilitating improved design and optimization of mechanically formed joints in thin-sheet applications.

KEYWORDS: finite element, clinching, pull-out

1. INTRODUCTION

1.1. Review of clinching simulation methods

Clinching is a mechanical joining technique used to permanently connect two or more sheet-metal components without the need for additional fasteners, welding, or adhesives. The process relies on localized plastic deformation: a punch forces the sheets into a die cavity, forming a characteristic interlock through material flow rather than through material removal or fusion. During forming, the sheets are plastically deformed to create a neck and an undercut, which together ensure mechanical engagement and load transfer between the components. Clinching is particularly attractive for lightweight structures because it enables joining of coated, dissimilar, or heat-sensitive materials while maintaining good fatigue performance and minimal thermal distortion. Due to its simplicity, low energy consumption, and suitability for automation, clinching has been widely adopted in automotive, appliance, and electronics manufacturing. However, despite its industrial relevance, the process is not commonly known outside specialized engineering fields, making a concise description essential for understanding the context and motivation of the present study.

The application of Finite Element Method (FEM) in analyzing mechanical clinching has evolved significantly over the last two decades, providing an increasingly accurate numerical framework for predicting material flow, stress distribution, and joint formation. Early comprehensive reviews, such as those by He [1] and Qin et al. [2], have established the theoretical basis for current simulation methods and highlighted the primary factors influencing clinched joint quality. He’s survey [1] outlines the transition from simplified axisymmetric models to fully 3D analyses, emphasizing the need for realistic constitutive laws and advanced contact formulations. Qin et al. [2] further systematize FEM approaches, categorizing modelling strategies by mesh type, material plasticity models, and frictional interfaces, serving as a benchmark for selecting appropriate modelling parameters in modern simulation studies.

Building upon this foundational work, several studies have focused on the detailed mechanics of joint formation. Lambiase and Di Ilio [3] investigated material flow during clinching using extensible dies, revealing the sensitivity of joint interlock to radial material displacement. Their work demonstrated how FEM can accurately capture deformation gradients and folding phenomena between sheet layers. Similarly, De Paula et al. [4] developed a numerical model to replicate sheet penetration and localized thickening during clinching, showing a strong correlation between simulation data and experimental observations.

Additional contributions have refined modelling resolution and realism. Jónás and Tisza [5] explored mesh refinement strategies and plasticity models to better capture localized strain accumulation, while Jagtap et al. [6] analyzed the effect of tool geometry variations on neck thickness and interlocking depth. These works highlight the ability of FEM not only to simulate the forming process but also to serve as a predictive tool for optimizing die design and process parameters. Collectively, the literature illustrates a clear progression from conceptual modelling to high-accuracy predictive simulation, forming the basis for the present study in which forming speed is introduced as a primary independent parameter influencing joint morphology and strength.

1.2. Pull-out strength and failure of clinched joints – literature review

A critical dimension of clinching research concerns the post-joining mechanical integrity of the connection, particularly its resistance to separation under tensile extraction, commonly expressed as pull-out strength. Early numerical contributions by Jomaa and Billardon [8] provided one of the first FEM-based frameworks for describing the progressive detachment of clinched sheet assemblies, establishing the significance of local stress concentration in the neck region as a determinant of joint failure initiation. Their modelling approach demonstrated that joint degradation proceeds through a sequence of shear-dominated and tensile-driven damage mechanisms, a conceptual foundation that has been extended in subsequent work.

Gronostajski et al. [7] refined this class of simulations by incorporating damage evolution laws into FEM formulations, enabling the prediction of maximum extraction force and the simulation of post-peak softening behaviour. Their results confirmed that geometric parameters, namely neck thickness and interlock depth, exert a dominant influence on peak pull-out load, validating FEM as a sufficiently accurate surrogate for destructive testing.

Further advancements are exemplified by Coppieters et al. [9], who integrated experimental validation with high-resolution numerical modelling to reproduce force–displacement curves with strong correlation precision. Their study highlighted the essential role of accurate material hardening models and interface friction representation, demonstrating that discrepancies between FEM and experimental pull-out responses are primarily attributable to insufficiently characterized strain-rate-dependent plasticity.

More recently, Martin et al. [10] expanded the analytical scope by incorporating pre-strain in the joint-forming region, reflecting the realistic manufacturing condition in which sheet material possesses residual deformation prior to joining. Their work revealed that pre-strain alters the stress distribution and modifies the failure path during extraction, thus providing a more physically realistic representation of joint performance.

Collectively, these studies confirm that FEM-based pull-out analysis has progressed from macro-failure prediction to increasingly sophisticated micro-mechanical characterization of failure evolution. Nevertheless, the literature exhibits a limited systematic investigation into the influence of *forming speed* - a parameter inherently linked to strain-rate-dependent material response on the final joint structure and extraction performance. This identified gap directly motivates the present study.

2. RESEARCH GAP AND ORIGINAL CONTRIBUTION OF THE PRESENT STUDY

Although FEM-based investigations of clinched joints have achieved substantial maturity in modelling joint formation geometry and post-joining mechanical performance, the influence of forming speed on the resultant connection has remained comparatively underexplored. Existing simulation frameworks have largely relied on quasi-static assumptions, employing forming velocities that implicitly approximate infinitely slow deformation. Such an approach neglects rate-dependent material behaviour, frictional heat effects, and dynamic flow characteristics that can manifest at elevated process speeds. The absence of systematic comparative studies across multiple controlled forming velocities represents a notable deficiency in current literature.

The present research addresses this gap by implementing a series of FEM simulations explicitly parameterized by forming speed, enabling the quantification of its effect on material displacement, strain localization, residual stress accumulation, and formation of the mechanical interlock. Furthermore, the study extends beyond joint creation to incorporate FEM-based pull-out simulation, providing a direct correlation between forming speed and resultant extraction force capacity. The integration of both formation-phase and failure-mode modelling within a unifying numerical framework constitutes a methodological advancement not sufficiently represented in prior studies.

3. METHODOLOGY AND MATERIAL MODEL DEFINITION

3.1. Simulation framework and model setup

The clinching process was simulated using the Finite Element Method within an explicit dynamic computational environment. The model consists of a deformable workpiece assembly comprising two metallic sheets and rigid tool components (punch, die, and blank holder). The tools were modelled as analytically rigid surfaces, thereby reducing computational expense while preserving geometric accuracy in material-contact interactions.

Boundary conditions were defined to reproduce the actual clinching sequence. The punch displacement was imposed as a controlled kinematic input, while the sheets were constrained to prevent lateral movement except for allowable material flow. Contact interactions between sheet–sheet and sheet–tool interfaces were represented via a penalty-based formulation incorporating frictional sliding, with the friction coefficient selected based on experimentally validated ranges reported in the literature.

A strategically refined mesh was applied to the joint region to capture strain localization and material separation phenomena. Convergence verification was performed to ensure that mesh refinement yielded stability in the predicted neck thickness, interlock depth, and residual strain distribution. Forming speeds were varied parametrically across simulations while all other process parameters remained constant.

3.2. Material model definition

The material used was DC04 and is classified according to EN 10130 as a cold-rolled low-carbon steel designed for forming applications. Its composition typically includes:

- very low carbon content (around 0.04% or below);
- low levels of phosphorus and sulfur;
- small additions of manganese.

This ensures excellent ductility, low yield strength, and high uniform elongation, making the material ideal for deep-drawing and complex sheet-metal forming operations.

Mechanical Properties (typical ranges):

- Yield strength: ~140–210 MPa
- Ultimate tensile strength: ~270–330 MPa
- Elongation at fracture: ≥ 38–40%
- Young’s modulus: ~210 GPa
- Poisson’s ratio: ~0.29–0.30

These characteristics allow the material to undergo large plastic deformation without cracking, which is crucial for processes such as stamping, clinching, and cold forming.

It exhibits mild strain-rate sensitivity, relevant when you vary forming speed. The mechanical response of the sheet material was modelled using an elastoplastic constitutive formulation incorporating strain-hardening and, where applicable, strain-rate sensitivity. At the elastic level, the material was assumed to follow linear isotropic elasticity characterized by Young’s modulus and Poisson’s ratio consistent with standard metallic sheet properties.

Plastic deformation was captured using a von Mises yield criterion combined with isotropic hardening. The mathematical model describing the material's behavior is as follows:

$$\sigma_F = C_1 \cdot e^{(C_2 \cdot T)} \cdot \varepsilon_p^{(n_1 \cdot T + n_2)} \cdot e^{\left(\frac{l_1 \cdot T + l_2}{\varphi}\right)} \cdot \dot{\varepsilon}_p^{(m_1 \cdot T + m_2)} \qquad (1)$$

where:

C_1, C_2, n_1, n_2, l_1, l_2, m_1, m_2 - parameters derived from the experimental data were used to calibrate the plasticity model. [Eq. (1)]. Table 1 shows the parameter values for the material employed in the modeling process, which were obtained through external methods, since Simufact Forming does not offer a procedure for their determination.

This formulation enables accurate representation of high-speed forming responses wherein the material exhibits increased resistance to deformation under higher strain-rate conditions, thereby directly linking forming speed to localized joint morphology.

Thermal–mechanical coupling was neglected in the current framework, as temperature rise during short-duration clinching is typically minimal. However, the constitutive formulation allows for future extension to thermally dependent effects if required.

The finite element model replicates the physical setup and is illustrated in Figure 1.

Table 1. *Plasticity model parameters*

Name	Abbr.	Value	
Temperature min	T	20.0	°C
Temperature max	T	200.0	°C
Strain min	φ	0.07	-
Strain max	φ	0.8	-
Strain rate min	$\dot{\varphi}$	1.0	1/s
Strain rate max	$\dot{\varphi}$	63.0	1/s
Parameter 01	c1	404.988	-
Parameter 02	c2	0.000134806	-
Parameter 03	n1	0.00156314	-
Parameter 04	n2	-0.00441433	-
Parameter 05	l1	0.000250938	-
Parameter 06	l2	-0.0394922	-
Parameter 07	m1	-0.000158195	-
Parameter 08	m2	0.0130388	-

The sheets were modeled as deformable bodies, while the tool and support components, considering the materials used (tool steel and carbon steel), were treated as rigid bodies. The two sheet-metal components were modeled as circular discs with a diameter of 40 mm and a thickness of 2 mm each. The punch used in the clinching process had a diameter of 15 mm, ensuring localized deformation and controlled material flow into the die cavity. The tool displacement velocity was set to 5, 10, and 15 mm/s and the stroke was set to 4.3 mm. An automatic remeshing function was employed to regenerate the mesh and allow the simulation to continue with the updated configuration. A total of 3576 Quad (10) elements were used to model the deformable sheets.

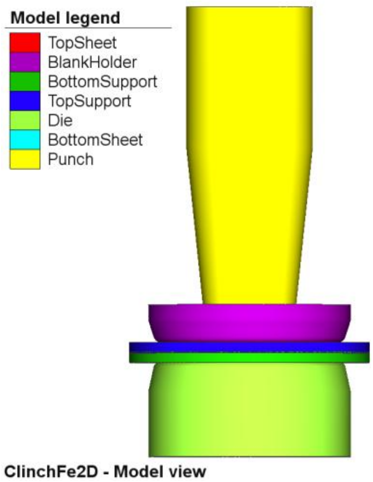

Fig. 1. *Axisymmetric 2D finite element model*

3.3. Pull-out simulation methodology

Following the formation-phase simulation, each joint configuration was subjected to numerical extraction testing. A displacement-controlled tensile separation was applied to one sheet while the opposing sheet was restrained. This approach reproduces the experimental pull-out test conditions described in prior studies. Force–displacement output curves were extracted, and failure was identified by loss of load-bearing capacity, indicated by peak force reduction and material separation.

4. RESULTS AND DISCUSSION

4.1. Stress and strain analysis in the clinching process

The FEM simulations revealed distinct differences in material response and joint morphology as a function of the imposed forming speed. The stress profiles within the joint exhibited pronounced localization in the neck region, with the maximum von Mises stresses consistently concentrated in the zone adjacent to the interlock. At a lower forming speed (5 mm/s), the stress distribution remained relatively uniform, indicating gradual material accommodation and reduced resistance to plastic flow (Figure 2). Figure 2 shows a more gradual and diffuse von Mises stress distribution. The material experiences lower peak stress concentrations and a smoother stress gradient from the punch-contact zone outward. The transition between stress zones is continuous, indicating slower material flow and reduced localized hardening. The interlock zone is formed with moderate compression, and the stress remains largely below 350 MPa except at minor isolated hotspots.

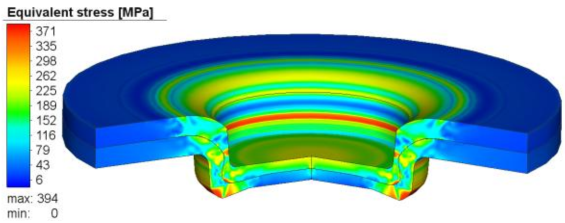

Fig. 2. *VM stress distribution at forming speed of 5 mm/s*

Figure 3 exhibits significantly sharper stress localization in the neck and interlock areas. The stress clusters more intensely in the red-orange band, indicating higher deformation resistance due to strain-rate effects. Peak values approach or reach ~396 MPa, with steeper stress gradients and more abrupt transition zones. This indicates stronger mechanical locking and a higher degree of elastic–plastic deformation at the joint interface.

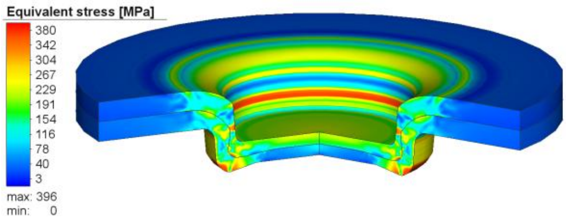

Fig. 3. *VM stress distribution at forming speed of 10 mm/s*

The equivalent stress distribution for the clinching process at 15 mm/s shows pronounced stress concentrations in the interlock formation zone and along the die radius, indicating intensified material flow resistance under this forming speed, while the surrounding sheet regions experience significantly lower stress levels.

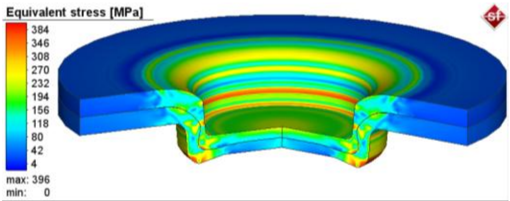

Fig. 4. *VM stress distribution at forming speed of 15mm/s*

Across the three forming speeds, 5 mm/s, 10 mm/s, and 15 mm/s, a gradual intensification of the von Mises stress distribution can be observed in the clinching zone. At 5 mm/s, the stress field remains relatively uniform, with moderate stress levels dominating the interlock region, indicating stable and well-distributed material flow. When the speed increases to 10 mm/s, localized stress concentrations begin to develop more distinctly around the die radius and interlock interfaces, suggesting that the material experiences reduced ability to redistribute deformation under higher forming rates. At 15 mm/s, these effects become more pronounced: peak stresses rise, stress bands sharpen, and the regions surrounding the neck and undercut exhibit stronger localization. Overall, the comparison shows that increasing forming speed leads to progressively higher stress magnitudes and reduced uniformity, confirming the strain-rate sensitivity of the clinching process and indicating a higher risk of localized deformation or failure at elevated forming velocities.

At the lower forming speed, the plastic strain field appears broader and more diffusely distributed. The strain is spread over a larger volume of material, particularly around the punch indentation region and along the sheet interface. The maximum recorded effective plastic strain reaches approximately 2.60, but the high–strain area (red zone) is thicker and more evenly distributed across the interlocking region. This suggests that the material had more time to flow and conform to the cavity under slow deformation, resulting in a more homogeneous strain distribution but slightly lower material compaction in the joint.

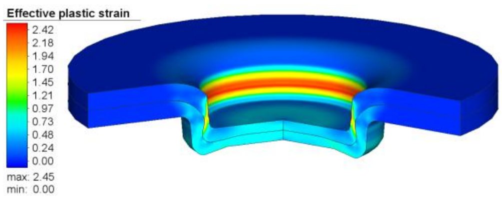

Fig. 5. *Plastic strain at 5 mm/s speed*

At the higher forming speed, the strain field becomes sharper and more concentrated. The peak plastic strain values are slightly lower (~2.45), but the zone of intense plastic strain is narrower and more sharply confined around the interlock radius and neck region. This indicates reduced material flow flexibility due to strain-rate effects. The deformation concentrates where the geometry enforces radial constriction, producing stronger mechanical locking.

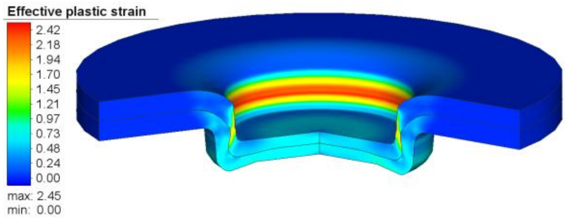

Fig. 6. *Plastic strain at 10 mm/s speed*

Together, the figures reveal a clear forming-speed–driven mechanism:

- At 5 mm/s, plastic strain is more distributed, reflecting the ductile, gradual flow of the sheet metal.
- At 10 mm/s, plastic strain is more localized, reflecting stiffer material response due to strain-rate sensitivity.
- The lower speed produces a smoother strain gradient and may help reduce potential micro-damage accumulation.
- The higher speed produces a concentrated deformation band at the interface, contributing to a more pronounced interlock and higher pull-out strength.
- Plastic strain localization at high speed coincides with stress concentration zones observed previously, confirming a consistent correlation between stress and plastic strain fields.

4.2. Stress Distribution During Pull-Out

In Figure 7, the equivalent (von Mises) stress field during the pull-out test shows pronounced localization along the interlock region and the lower sheet, especially at the radius where the sheets start to separate. High stress values (yellow–red range, up to ~390 MPa) are concentrated at the inner flank of the undercut and in the bent zone of the lower sheet. The upper sheet, away from the joint, remains mostly in the blue–green range, indicating limited plastic reloading. The stress pattern suggests that failure initiates by shear and bending in the lower sheet near the interlock, followed by progressive opening of the joint.

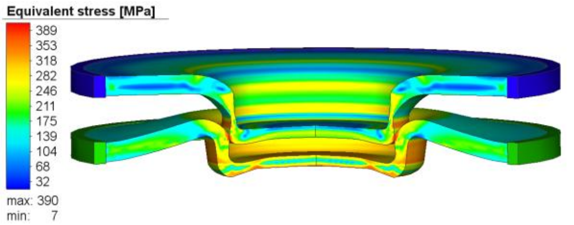

Fig. 7. *VM stress in pull-out simulation, 5 mm/s speed*

In Figure 8, corresponding to the joint formed at the higher forming speed, the stress distribution during pull-out is more continuous and slightly more intense along the entire interlock circumference and in the lower sheet. Peak values reach ~393 MPa, with a wider yellow–orange band at the undercut and along the lower sheet ligament. The load is transferred more effectively through the interlocking zone, and the highly stressed region extends further along the separation interface, indicating a more robust mechanical engagement.

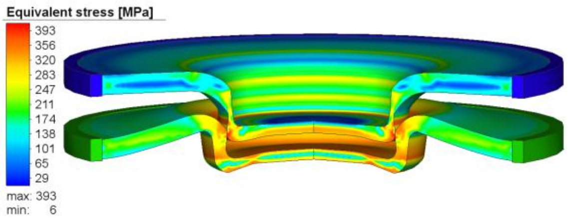

Fig. 8. *VM stress in pull-out simulation, 10 mm/s speed*

The von Mises stress distribution during the pull-out simulation at 15 mm/s shows pronounced stress concentrations along the interlock region and at the interfaces between the upper and lower sheets, indicating that these zones experience the highest resistance during separation. The elevated stress levels in the necking and undercut areas suggest that material failure or tearing would likely initiate here, while the remaining sheet regions are subjected to significantly lower stress, reflecting minimal involvement in the pull-out load transfer.

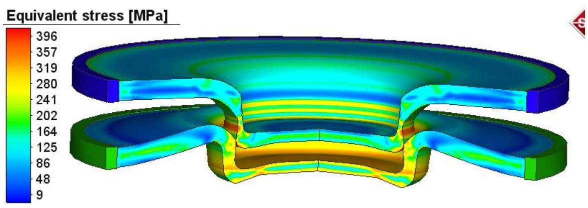

Fig. 9. *VM stress in pull-out simulation, 15 mm/s speed*

When comparing the pull-out simulations for the three forming speeds, 5 mm/s, 10 mm/s, and 15 mm/s, it becomes evident that all joints develop their maximum von Mises stresses in the same critical regions, namely the neck zone and the interlock area. This consistent stress localization confirms that pull-out failure is primarily governed by bending-dominated deformation and shear concentration within the lower sheet. Despite this common failure mechanism, the stress magnitudes and distribution patterns differ noticeably across the forming speeds.

At 5 mm/s, the joint shows a narrow and discontinuous stress concentration around the interlock, indicating a weaker mechanical engagement and lower pull-out strength. At 10 mm/s, the stress field becomes broader and more uniform, reflecting a better-formed interlock with more efficient load transfer and increased extraction resistance. At 15 mm/s, stress levels intensify further and penetrate deeper into the lower sheet, producing the stiffest interlock but also the most severe stress localization, suggesting a strong yet more brittle failure behavior.

For the joint formed at 5 mm/s, the Z-force curve, Figure 10, shows a rapid initial rise, followed by a stable plateau around ~3.3–3.35 kN during the holding phase. In the separation stage, the force decreases gradually, exhibiting multiple oscillations. This indicates that failure occurs progressively, with the material yielding through a combination of shear and plastic deformation in the interlock region. The gradual decay of force suggests a more ductile joint separation mechanism, with redistribution of stresses as the sheets begin to disengage.

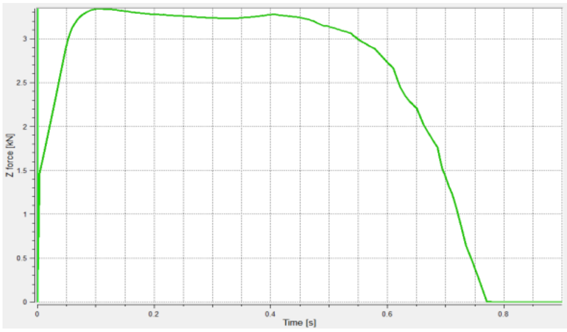

Fig. 10. *Force–time response during numerical pull-out tests for joints formed at 5 mm/s*

For the joint formed at 10 mm/s, the curve displayed in Figure 11 shows the same maximum force level (~3.35 kN), but the plateau is more stable and uniform. During pull-out, the force drop is sharper and more coherent, with fewer fluctuations. This behavior indicates a more rigid mechanical interlock with a well-defined failure onset.

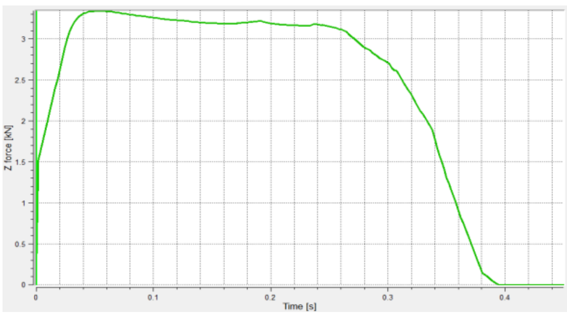

Fig. 11. *Force–time response during numerical pull-out tests for joints formed at 10 mm/s*

The force–time curve for the joint formed at 15 mm/s shows a rapid increase in extraction force at the beginning of the pull-out test, indicating immediate engagement of the interlock. The force quickly reaches a peak value slightly above 3.3 kN, representing the maximum mechanical resistance of the joint. Following this peak, the force remains relatively stable for a short interval, suggesting sustained load transfer through the interlock. However, after approximately 0.18–0.20 s, the force starts to decline progressively, reflecting the onset of local damage and loss of structural integrity within the lower sheet.

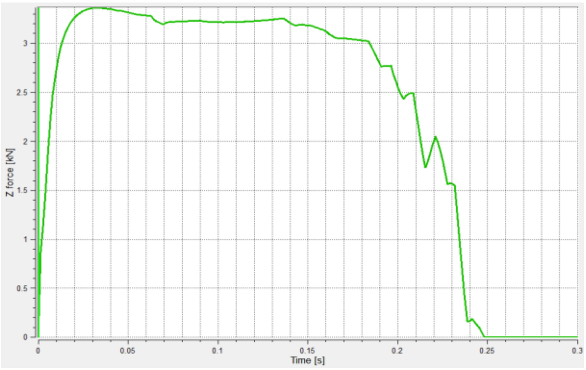

Fig. 12. *Force–time response during numerical pull-out tests for joints formed at 15 mm/s*

5. CONCLUSIONS

This study examined the influence of forming speed on the clinching process using finite element simulations, with particular focus on stress evolution, plastic strain distribution, joint morphology, and pull-out resistance. The results demonstrate that forming speed is a critical process parameter that significantly affects both the formation of the interlock and the mechanical performance of the joint.

Lower forming speed (5 mm/s) promotes broader and more uniformly distributed plastic deformation, resulting in smoother material flow into the die cavity. This produces a more compliant interlock structure with gradual stress dissipation during pull-out, indicating a more ductile failure mechanism. In contrast, medium forming speed (10 mm/s) introduces strain-rate effects that localize deformation and intensify stress accumulation in the neck and interlock region. The resulting joint exhibits stronger mechanical engagement and a more abrupt force drop during extraction, consistent with a more rigid and structurally efficient interlock. High forming speed (15 mm/s) further amplifies strain-rate effects, leading to sharply localized plastic deformation and the highest stress concentrations in the neck and interlock region. The resulting joint develops the strongest mechanical locking and peak pull-out force, but failure occurs through a sudden and highly localized loss of load-carrying capacity, indicating a stiff interlock with a more brittle-like fracture behaviour.

The correlation between effective strain fields, von Mises stress distributions, and extraction force curves reveals that faster forming enhances joint locking efficiency and improves resistance to pull-out. These findings provide valuable insight for industrial process optimization, suggesting that controlled increases in forming speed can improve joint integrity without requiring changes in tool geometry or material properties.

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