Modeling and Simulation of Sheet Metal Deformation for the Generation of Folded Surfaces

Valentin Corzanu
PhD student
University of Craiova
Faculty of Mechanical
Romania

Alina Duta
Teaching
University of Craiova
Faculty of Mechanical
Romania

Simona-Mariana Cretu
Teaching
University of Craiova
Faculty of Mechanical
Romania

Andrei Corzanu
PhD student
University of Craiova
Faculty of Mechanical
Romania

Misa Stojicevic
Assistant Professor
University of Belgrade
Faculty of Mechanical
Serbia

Free-form folded sheet structures represent an emerging class of lightweight systems in which geometric deformation is used to transform planar materials into complex three-dimensional configurations. Although curved folding concepts have been extensively investigated from geometrical and kinematic perspectives, the influence of curved folding path topology on the mechanical response of metallic sheets remains insufficiently quantified. This study presents a numerical investigation of the deformation behaviour of aluminium sheets containing different curved folding path configurations. Three geometrical configurations were analysed: a single curved folding path, two intersecting curved folding paths and three intersecting curved folding paths. Five sheet thicknesses were evaluated under a uniform in-plane edge pressure of 10 MPa. All models were developed using a parametric CAD approach and analysed under identical material properties, geometrical dimensions, and loading conditions in order to isolate the influence of folding topology. The effects of sheet thickness and boundary condition definition were investigated using complementary numerical approaches based on Altair SimSolid and Altair HyperMesh. The results obtained for displacements and Von Mises stress are strongly dependent on the overall configuration and sheet thickness. Mathematical regression models $D_{max}(C,t)$ and $\sigma_{max}(C,t)$ were established to express global displacement and Von Mises equivalent stress as quadratic functions of folding topology (C) and thickness (t). However, additional intersecting folding paths generate higher local stress concentrations, particularly in regions where multiple deformation mechanisms interact. The study also highlights the importance of boundary condition definition in predicting the deformation behaviour of curved folded structures. Fully constrained folding paths may introduce artificial stress concentrations, while localized and distributed constraints provide a more realistic representation of the physical deformation mechanism. The results establish a systematic relationship between curved folding topology, structural stiffness, stress distribution, and constraint definition. The proposed methodology can support the design and optimization of lightweight free-form folded structures for mechanical engineering, architectural, and industrial applications.

Keywords :*curved folding; free-form surfaces; folded sheet metal; alumi–nium alloy; numerical simulation; finite element analysis; meshless simu–lation; structural behaviour.*

1. INTRODUCTION

The development of lightweight three-dimensional stru–ctures from initially flat materials represents an impor–tant research direction in mechanical engineering, arc–hitectureand industrial design. Recent advances in computational geometry, computer-aided design (CAD), and digital manufacturing have enabled the generation of complex free-form surfaces with applications in aerospace structures – lightweight stiffened panels, automotive components – body panels with improved crash energy absorption, architectural shells – free-form facades and deployable structures, and customized products as for industrial design – customized light–weight products.

Free-form surfaces are characterized by complex spatial configurations that cannot be described using conventional analytical geometries such as planes, cy–linders, cones, or spheres. Their representation generally relies on advanced modelling techniques, including non-uniform rational B-splines (NURBS), subdivision sur–faces, and mesh-based approaches, which allow accu–rate generation and manipulation of complex geomet–rical forms [1,2].

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Correspondence to: Valentin Corzanu, PhD Student, University of Craiova, Faculty of Mechanics, 107, Calea Bucuresti, Craiova, 200478, Romania.
E-mail: corzanu.valentin.a7v@student.ucv.ro
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An important class of free-form structures is represented by folded surfaces, where initially planar materials are transformed into three-dimensional configurations through controlled deformation. Folding-based design principles have received increasing attention because they provide lightweight solutions, structural efficiency, and the possibility of creating adaptive or deployable systems.

Origami-inspired structures have demonstrated that geometric transformations can be used to modify mechanical behaviour without significant changes in material quantity. However, classical origami approaches are mainly based on straight folding lines, while curved folding introduces nonlinear deformation paths that generate more complex geometrical and mechanical responses.

Curved folding structures are governed by the interaction between crease geometry, material properties, sheet thickness, and boundary conditions. Unlike rigid origami models, real thin sheets undergo elastic deformation, and the resulting shape is influenced by bending stiffness, stress distribution, and local geometric constraints [3–7]. Therefore, the transition from theoretical curved folding concepts to engineering applications requires detailed mechanical analysis.

Previous studies have investigated curved-line folding for deployable structures and architectural applications. Vergauwen et al. demonstrated the potential of curved folding for generating complex deployable configurations through digital modelling techniques [3]. More recent investigations have focused on the mechanics of curved creases, showing that crease geometry influences deformation modes, stiffness variation, and coupling effects between multiple folding paths [5–7].

The application of curved folding principles to thin metallic sheets represents an attractive approach for producing lightweight free-form structures. In such systems, local geometric modifications can significantly influence global structural behaviour. Studies on bending-active shell structures have demonstrated that thin sheets can be transformed into load-bearing three-dimensional configurations by controlling curvature and folding mechanisms [8].

However, metallic folded structures differ significantly from idealized origami models because they involve material elasticity, stress accumulation, manufacturing limitations, and possible local failure mechanisms. Consequently, numerical simulation becomes essential for predicting deformation behaviour and optimizing structural performance.

Finite element methods (FEM) are widely used for analysing sheet metal forming and bending processes because they provide information regarding displacement fields, stress distribution, and potential failure regions [9,10]. The reliability of these simulations depends on several factors, including material constitutive models, element formulation, mesh quality, and boundary condition definition. Previous studies have successfully employed finite element analysis to predict the onset of plastic deformation under complex loading conditions, demonstrating the capability of numerical methods to accurately identify yielding phenomena and permanent deformation in metallic structures [11]. Although extrusion and sheet folding are different forming operations, both involve complex elastoplastic material behaviour that can be effectively analysed using numerical simulation. Hrudkina [12] demonstrated the successful application of computational modelling for predicting deformation characteristics and process parameters in a cold metal forming process, confirming the versatility of numerical approaches for investigating material response under large deformation conditions. These studies underline the broader applicability of FEM-based techniques to different metal forming processes, including the deformation mechanisms involved in curved folding of thin metallic sheets.

Younas et al. demonstrated that advanced finite element formulations and appropriate material models are essential for accurately predicting complex deformation states in sheet metal forming processes [13]. Furthermore, optimization methods based on numerical simulation, design of experiments, and response surface methodologies have been successfully applied to determine optimal forming parameters and improve manufacturing efficiency [14]. Although theoretical calculations and finite element simulations provide valuable support by enabling the prior estimation of stresses and strains within acceptable limits, practical applications often involve secondary phenomena, such as local buckling or instability, that are difficult to predict using numerical models alone. Consequently, experimental validation remains an important complement to computational analysis. In this context, Braut et al. [15] proposed a simple and rapid experimental method for measuring strain in sheet metals, highlighting the importance of reliable deformation measurements for validating numerical predictions and improving the accuracy of structural analyses.

Besides geometry and material modelling, process parameters may significantly influence simulation results. Factors such as friction conditions, surface characteristics, and deformation rate affect the accuracy of sheet metal forming predictions and must be considered when developing reliable numerical models [16].

For complex free-form geometries, conventional finite element analysis may require considerable preprocessing effort due to the need for appropriate mesh generation, element selection, and local refinement. Meshless structural simulation approaches represent an alternative solution by allowing the evaluation of CAD-based models with reduced preprocessing requirements. Altair SimSolid is based on an external approximation approach that enables rapid structural assessment while maintaining accuracy for many linear static analyses [17].

Although significant progress has been achieved in the fields of origami-inspired structures, curved crease mechanics, and numerical modelling of sheet metal deformation, several aspects remain insufficiently investigated.

Most existing studies concerning curved folding structures focus mainly on:

- geometrical generation methods;
- mathematical description of curved creases;
- kinematic analysis;
- deployable architectural structures.

The mechanical influence of curved folding topology on metallic sheets subjected to controlled loading conditions has received comparatively less attention.

In particular, the effect of increasing the number of intersecting curved folding paths on structural stiffness, deformation behaviour, and stress distribution has not been systematically evaluated under identical material, geometric, and loading conditions.

Previous investigations have demonstrated that individual folding patterns can modify the mechanical response of thin structures; however, a direct comparative analysis between one, two, and three intersecting curved folding paths is still lacking. Such a comparison is important because the interaction between multiple curved paths may simultaneously increase structural stiffness and generate critical stress concentration regions.

Therefore, this study addresses the following research question:

How does the topology of curved folding paths influence the mechanical response of thin metallic sheets subjected to controlled static loading?

To answer this question, a numerical investigation was performed on aluminium alloy sheets containing different curved folding configurations.

The analysed structures consist of:

- a single curved folding path;
- two intersecting curved folding paths;
- three intersecting curved folding paths.

All configurations were generated using the same initial sheet dimensions, material properties, and loading conditions, allowing the influence of folding topology to be isolated.

The main objectives of this research are:

1. to evaluate the influence of the number of curved folding paths on global deformation behaviour;
2. to analyse the relationship between folding topology and Von Mises stress distribution;
3. to investigate the influence of boundary condition definition on the predicted deformation mechanism;
4. to establish an efficient numerical methodology for analysing free-form folded metallic structures.

The main contributions of this study are:

(I) A systematic numerical comparison of three curved folding path configurations under identical loading conditions.

(II) Quantitative evaluation of the relationship between folding topology, structural stiffness, and stress concentration.

(III) Demonstration that boundary condition definition significantly affects the predicted mechanical response of curved folded sheets.

(IV) Development of a combined simulation strategy based on meshless structural analysis and finite element modelling for the investigation of free-form folded structures.

The obtained results provide new insights into the mechanical behaviour of curved folded metallic sheets and contribute to the development of lightweight free-form structures for mechanical engineering, industrial design, and architectural applications.

Unlike previous studies that focused primarily on geometric origami models or limited crease configurations, our work establishes a unified simulation framework for curved folding in metallic sheets under controlled loading. This directly addresses the lack of systematic analysis of intersecting curved paths and their influence on stress distribution.

This paper aims to perform a static analysis of a deformed aluminium sheet in order to obtain free-form folded surfaces with complex shapes. The study starts from the application of a simple geometric curve on the surface of a metal sheet, followed by the analysis of more elaborate configurations involving two or three intersecting curves. In all cases, the initial dimensions of the support sheet remain constant to ensure a comparable basis between the different models.

To perform a relevant comparative analysis, all models are subjected to the same external load but under different constraint conditions, and the results obtained from the simulations for stress distribution and displacements were studied.

The simulations and structural analysis were performed using the Altair software suite. In particular, Sim Solid was used for a quick and meshless analysis, which is effective for complex geometries, and Hyper Mesh was used for model preparation and detailed finite element meshing. Together, these solutions enabled an accurate and comparative evaluation of the deformation behaviour of each configuration analysed.

2. MATERIALS AND NUMERICAL METHODOLOGY

The numerical investigation was developed to evaluate the influence of curved folding path topology on the mechanical behaviour of free-form folded aluminium sheet structures. The proposed methodology combines parametric CAD modelling, meshless structural simulation, and finite element analysis in order to determine the relationship between folding geometry, deformation behaviour, and stress distribution.

The study was designed as a comparative numerical investigation. All analysed models were generated using the same initial sheet dimensions, material properties, and loading conditions. Therefore, the influence of curved folding topology could be evaluated independently of other parameters.

The investigated variables were:

- number of curved folding paths;
- sheet thickness;
- boundary condition definition.

The numerical workflow consisted of five main stages:

1. geometric modelling of folded sheet configurations;
2. definition of material properties;
3. application of boundary conditions and external loading;
4. structural simulation;
5. evaluation of displacement and Von Mises equivalent stress distributions.

2.1 Numerical investigation workflow

A parametric modelling and simulation workflow was developed for the analysis of free-form folded sheet structures.

The complete procedure is presented in Figure 1.

The use of a parametric approach allows the modification of geometric parameters while maintaining the same reference conditions. This is essential for comparative studies where the influence of a single design variable must be isolated.

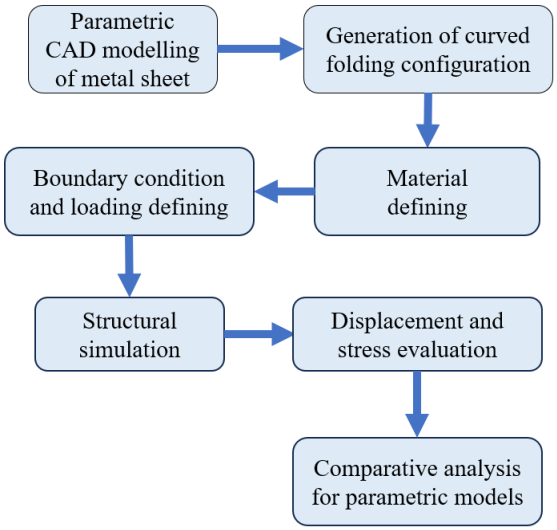


Figure 1. Numerical investigation workflow

2.2 Geometrical modelling of curved folding configurations

The analysed structures consist of square aluminium sheets with dimensions in mm: 251×251

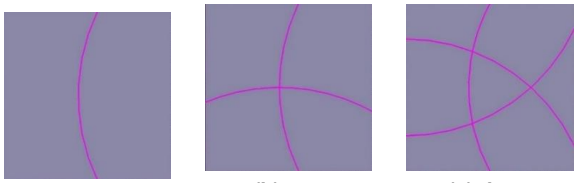
Three different thickness values were considered in mm: 0.5, 0.7, 1, 1.5 and 2

The influence of curved folding topology was investigated using three configurations (Figure 2):

- Configuration C1: one curved folding path;
- ConfigurationC2: two intersecting curved folding paths;
- Configuration C3: three intersecting curved folding paths.

The radius of the curved paths and the initial sheet dimensions were maintained constant for all models.

This approach ensures that variations in mechanical response are generated only by changes in folding topology.



(a) one curved folding path (C1); **(b) two intersecting curved folding paths (C2);** **(c) three intersecting curved folding paths (C3).**

Figure 2. Investigated curved folding path configurations

2.3 CAD modelling procedure

The three-dimensional models were generated using Autodesk Inventor through a parametric modelling approach.

The modelling sequence consisted of:

1. creation of the initial flat sheet geometry;
2. definition of curved folding paths;
3. creation of a triangular folding channel profile, the depth of the channel was chosen to be 1/3 of the sheet thickness;
4. generation of the channel using a sweep operation along each curved path. The channel profile was defined as an isosceles triangle with an apex angle of:

The purpose of the channel is to locally modify the stiffness distribution and to guide the deformation process during loading.

The final CAD models were exported in STEP format and subsequently imported into the simulation environments.

2.4 Material properties

All numerical simulations were performed using Aluminium Alloy 2024-T6.

This alloy was selected due to its high specific strength and its frequent use in lightweight structural applications.

The material was considered homogeneous and isotropic.

The mechanical properties used in the simulations are presented in Table 1.

Table 1. Mechanical properties of Aluminium Alloy 2024-T6

Elasticity modulus [MPa]	72400
Poisson's ratio	0.33
Density [g/cm^3]	2.78
Tensile Strength Ultimate [MPa]	427
Tensile Strength Yield [MPa]	345

The selected mechanical parameters are consistent with numerical studies of aluminium sheet deformation processes [13].

2.5 Definition of loading and boundary conditions

All models were analysed under identical static loading conditions.

A uniformly distributed pressure of 10 MPa was applied on the four lateral surfaces of each sheet.

The loading level was selected to produce measurable deformation while maintaining predominantly elastic behaviour.

Boundary conditions represent a critical aspect of curved folding simulation because they determine how the structure is allowed to deform.

Two constraint approaches were investigated.

For the fully constrained curved folding paths,in the first simulation stage, all degrees of freedom of the points defining the curved folding paths were constrained (Figure 3a).

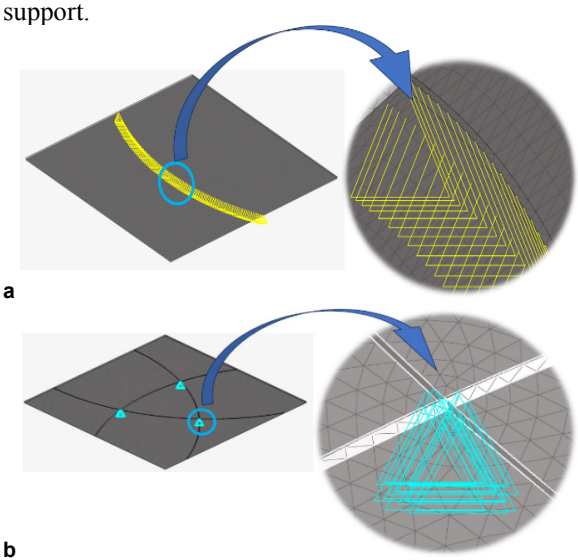
This condition represents a highly restricted deformation mechanism and was used as a reference case.

For the second case namely localized constraint strategy, the constraints were applied only at characteristic locations:

- for the single curved folding path configuration, the central points of the curve were constrained;
- for configurations with multiple curves, the intersection points between curved paths were constrained (Figure 3b).

The remaining points along the curves were allowed to deform freely.

This approach better represents the physical beha–viour of curved folding structures, where the crease path guides deformation but does not behave as a fully fixed support.



a

b

Figure 3. Boundary condition strategies:(a) fully constra–ined curved folding path; (b) distributed multi-node constraints.

2.6 Structural simulation methods

Two complementary numerical approaches were emp–loyed, for reasons of accuracy and efficiency of the simulation. So, Altair SimSolid was used to perform the simulation where the whole curve was constrained, and Altair HyperMesh was used for multi-node constraints.

2.6.1 Meshless structural analysis using Altair SimSolid

SimSolid directly uses CAD geometry for structural analysis and does not require conventional manual mesh generation [17].

This approach applied for the three configurations with the whole curve constrained reduces preprocessing time and enables rapid comparison during preliminary development stages.

The obtained results included:maximum and mini–mum displacement, maximum and minimum Von Mises equivalent stress.

2.6.2 Finite element analysis using Altair HyperMesh

A detailed finite element analysis was performed using Altair HyperMesh.

The CAD models were imported in STEP format and discretized using tetrahedral elements.

A global mesh size of 3 mm was initially applied.

Local refinement was introduced in regions with increased geometrical complexity, particularly near the intersection zones of curved folding paths.

The curvature-based refinement parameters were: minimum size factor: 0.1 mm;feature angle: 30° and growth rate: 1.3 (Figure 4).

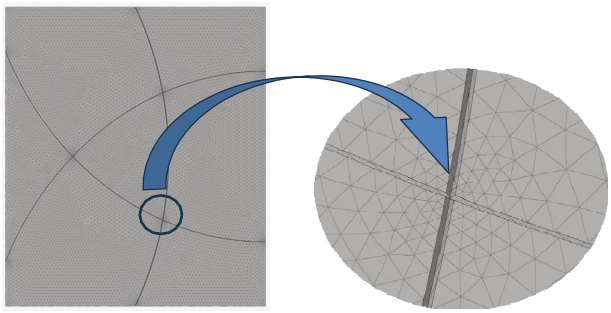


Figure 4. Curvature-based mesh refinement in the intersection region of curved folding paths

The refined mesh improves the representation of local stress gradients and allows a more accurate evalu–ation of critical regions.

2.7 Simulation matrix

The complete numerical investigation included:

- 3 curved folding configurations;
- 3 sheet thickness values;
- 2 boundary condition strategies. The analysed parameters are summarized in Table 2.

Table 2. Numerical investigation parameters

Parameter	Values
Sheet dimensions[mm]	251 × 251
Thickness[mm]	0.5, 0.7, 1, 1.5, 2
Curved folding paths	1, 2, 3
Material - Aluminium alloy	2024-T6
Applied pressure[MPa]	10
Simulation methods	Altair SimSolid
	Altair HyperMesh
Evaluated parameters	Displacement
	Von Mises stress

3. Results AND Discussion

The numerical simulations were performed in order to evaluate the influence of curved folding path topology on the mechanical response of thin aluminium sheets. The analysis focused on two main aspects:

- global structural behaviour, evaluated through displacement distribution;
- local mechanical response, evaluated through Von Mises equivalent stress distribution.

The results obtained from the two numerical app–roaches, Altair SimSolid and Altair HyperMesh, were analysed comparatively in order to identify the influ–ence of geometric configuration, sheet thickness, and boundary condition definition.

3.1 Altair SimSolid simulation of the folding processes

3.1.1 Results for displacement

For the chosen configurations and thicknesses, with Altair SimSolid simulation of the folding processes, the results obtained for the maximum and minimum displacements are highlighted in Table 3.

Table 3. Maximum displacement obtained from Altair SimSolid simulations

Configuration	Thickness [mm]	Displacement min [mm]	Displacement max [mm]
	0.5	3.1062E-06	1.6210E+00
	0.7	3.7685E-06	1.2316E+00
	1	5.3188E-06	9.4515E-01
	1.5	4.0305E-06	9.2645E-01
	2 (Fig. 5)	8.8485E-07	6.8742E-01
	0.5	5.1920E-07	1.1878E+00
	0.7	3.0429E-09	1.1222E-01
	1	1.9698E-09	2.8465E-01
	1.5 (Fig. 6)	3.1359E-07	7.4570E-02
	2	1.0143E-09	1.5042E-01
	0.5	1.2005E-09	2.7701E-01
	0.7	5.4363E-09	1.4183E-01
	1 (Fig. 7)	2.5137E-09	1.4507E-01
	1.5	3.5409E-07	9.2140E-02
	2	3.5506E-07	6.7350E-02

- **Influence of curved folding topology on global deformation behaviour**

The first analysis considered the influence of the number of curved folding paths on the global deformation of the sheet. Three configurations were compared:

- C1 – one curved folding path;
- C2 – two intersecting curved folding paths;
- C3 – three intersecting curved folding paths.

The simulations were performed using identical material properties, sheet dimensions, and loading conditions.

For the 15 simulated cases, displacement maps were obtained, from which we selected one situation for each configuration. The obtained displacement fields are presented in Figures 5–7.

The results show that the maximum displacement decreases with increasing number of curved folding paths because the curves act as stiffeners. They increase the moment of inertia of the section, making the plate much more resistant to bending.

For the single curved folding configuration, the deformation is concentrated around the main folding path, allowing larger global movement of the sheet.

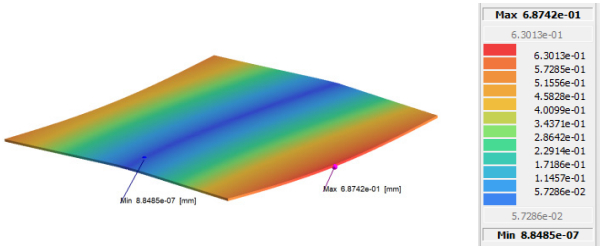


Figure 5. Displacement distribution for configuration C1, t = 2 mm

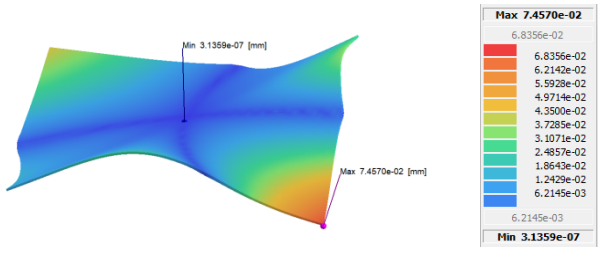


Figure 6. Displacement distribution for configuration C2, t = 1.5 mm

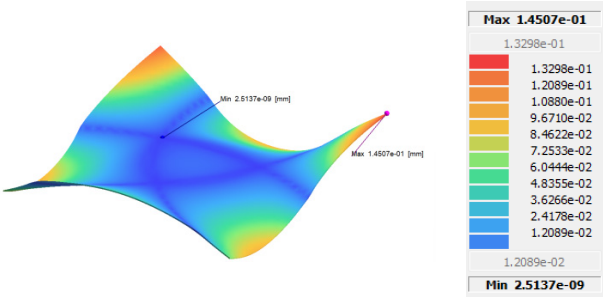


Figure 7. Displacement distribution for configuration C3, t = 1 mm

When two or three intersecting curves are introduced, the sheet is divided into smaller deformation domains. This geometric subdivision increases structural stiffness and limits the propagation of deformation.

The obtained results indicate that curved folding topology acts as a passive stiffening mechanism.

For identical thickness values, the three-curve configuration presents the lowest displacement values.

This behaviour can be explained by the increase in geometrical constraints generated by the intersection of multiple curved paths.

- **Influence of sheet thickness on displacement reduction**

The effect of thickness variation was analyzed for all geometric configurations.

Increasing the thickness produces a significant reduction in displacement for all analyzed configurations. Physically, the bending stiffness of a plate is proportional to the thickness to the cube (t^3). So, a thicker plate will deform much harder. A small anomaly is observed at C2, t = 0.7 mm, where the value drops sharply to 0.112 mm, then increases to 0.284 mm for 1 mm. This is most likely a change in the deformation mode in the simulation - buckling - or a peculiarity of the constraints, but it does not spoil the macro trend of the obtained data.

Using the mathematical regression method (curve fitting), a formula can be determined to predict the maximum deformation depending on the number of curves (C) and the thickness (t).

Isolating the variable "number of curves" (n), it is calculated with the average of the maximum deformations for each configuration to see how the geometry stiffens the part. Thus:

For C1: the average is ≈1.082 mm

For C2: the average is ≈0.362 mm

For C3: the average is ≈0.145 mm

A steep decrease is observed. We can also approximate this stiffening by a polynomial equation of degree 2 of the formula (1):

$$D = aC^2 + bC + c \tag{1}$$

Solving the system for these averages, we obtain the basis of the formula (2):

$$D_{med}(C) \approx\sim 0.25C^2 - 1.47C + 2.3 \tag{2}$$

The isolation of the "thickness" variable (t), is calculated taking into account the average deviation (Δ) generated by each thickness from the standard beha–

viour. The thicker the part, the more negative the deviation should be (pulls the deformation down).

The final formula (3) for the maximum deformation (D_{max}) is obtained by combining the two components.

$$D_{\max}(C,t) \approx \left(0.25C^2 - 1.47C + 2.3\right) + \Delta t \qquad (3)$$

The formula is a very good approximation of reality. It mathematically demonstrates to you that adding new curves massively "slows" the deformation, and increasing the thickness acts as an additional, predictable factor to reduce it.

3.1.2 Von Mises equivalent stress analysis

For all simulated cases, Von Mises equivalent stress maps were obtained, from which we selected one situation for each configuration. The Von Mises equivalent stress maps are presented in Figures 8–10.

Table 4. Maximum Von Mises obtained from Altair SimSolid simulations

Configuration	Thickness [mm]	Von Mises min [MPa]	Von Mises max [MPa]
	0.5	2.7070E+00	2.1215E+01
	0.7 (Fig. 8)	1.9106E+00	1.9643E+01
	1	3.1651E+00	2.7103E+01
	1.5	1.9006E+00	1.7797E+01
	2	2.6205E+00	2.0854E+01
	0.5	1.7976E-01	2.7711E+01
	0.7 (Fig. 9)	1.2012E-01	2.5518E+01
	1	6.3361E-01	2.9703E+01
	1.5	1.6664E-01	2.2530E+01
	2	9.7345E-01	2.2086E+01
	0.5	6.3778E-02	3.3417E+01
	0.7	5.0572E-02	3.5375E+01
	1 (Fig. 10)	1.2655E-01	3.5266E+01
	1.5	1.2021E-01	3.1841E+01
	2	4.1863E-02	3.3605E+01

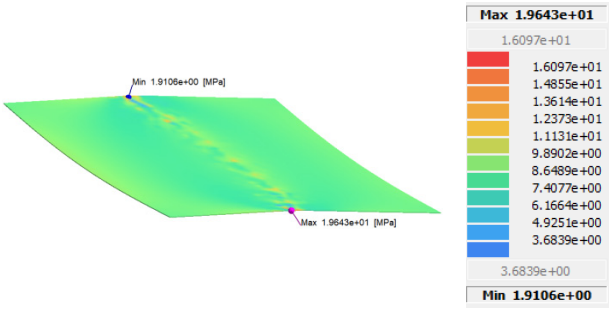


Figure 8. Von Mises stress distribution for configuration C1, t = 0.7 mm

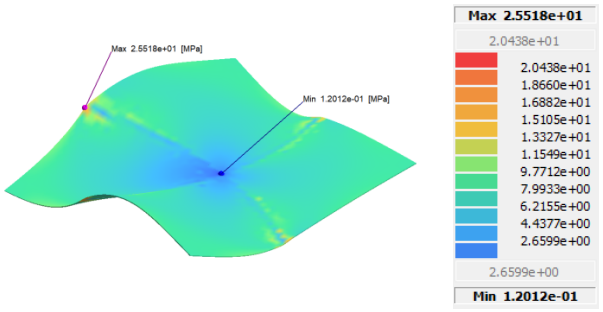


Figure 9. Von Mises stress distribution for configuration C2, t = 0.7 mm

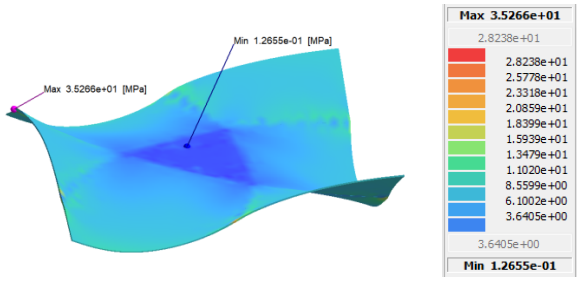


Figure 10. Von Mises stress distribution for configuration C3, t = 1 mm

The fact that the values for Von Mises max fluctuate seemingly chaotically indicates that this is not a uniform distribution of stresses, but rather complex local phenomena specific to Finite Element Analysis (FEA/ MEF).

It is observed that the variation with thickness is not linear or decreasing. Regarding the variation with configuration, it is observed that as you add more curves (ribs/stiffeners), the overall maximum stress increases, instead of decreasing.

These results are almost certainly due to the way in which the simulation software calculates the maximum stresses in the intersection areas (geometry) and the way in which the part is discretized (mesh).

The intersection point acts as a major stress concentrator. Although the structure as a whole becomes stiffer and the average (nominal) stress probably decreases, the stress at an infinitesimal point in the intersection area will increase massively. This is why the 3-curve configuration has the highest maximum stresses.

The automatically generated finite element mesh can generate a distorted or too sharp finite element in the area of the bends, which creates a singularity. For this reason, the software reports this isolated node as "Von Mises max", although the rest of the part is much less stressed.

Although increasing the number of curved bending paths improves stiffness, it also changes the stress distribution.

The stress distribution indicates that the highest values are located near:

- the curved bending paths;
- the intersections between the bends;
- the transitions between the deformed and undeformed regions.

For the configuration with a single curved bend, the stress field is relatively distributed along the bending region.

In the case of two intersecting bends, the interaction between the deformation fields generates higher stress gradients near the intersection area.

The three-curve configuration exhibits the highest local stress values, as multiple deformation mechanisms converge in a small area.

This result confirms that increasing the complexity of the folding produces a simultaneous improvement in stiffness and an increase in local stress concentration.

As the thickness increases, the relative stiffness between the curved and flat areas changes. The maximum stress could "move" from a bending area of the plate directly to the base of the curve (in the shear zone), completely changing the law of variation.

Since the data are not linear, the variation of the maximum Von Mises stress (σ_{max}) can be described as a function composed of two components: one dependent on the number of curves (C) and a fluctuating component dependent on the thickness (t). The variation law mathematically deduced from the data obtained by simulation has the same configuration as in the case of displacements, the stress increases nonlinearly (accelerated) with the addition of new curves. This increase is perfectly modelled by a polynomial function of degree 2 (quadratic equation). Deducing the coefficients, the basic variation law is given by formula (4):

$$\sigma_{med}(C) \approx\sim 2.1C^2 - 2.1C + 21.3 \quad (4)$$

where $C \in \{1,2,3\}$ represents the number of configurations/curves.

The variation as a function of thickness (t) does not follow a continuous monotonic function, but has an oscillating character.

Combining the two observations, the law of variation of the maximum Von Mises equivalent stress for the data set is defined by the following empirical formula (5):

$$\sigma_{\max}(C,t) \approx \left(2.1C^2 - 2.1C + 21.3\right) + \Delta(t) \quad (5)$$

The obtained trends demonstrate an important design compromise. Increasing the number of curved folding paths:

- decreases global deformation;
- increases structural stiffness;
- increases local stress concentration.

Therefore, curved folding topology must be optimized according to the required structural function. For applications requiring high rigidity, multiple curved paths provide advantages.

However, for applications involving cyclic loading or plastic deformation, stress concentration regions must be carefully evaluated.

3.2 Altair HyperMesh simulation of the folding processes

For the three-curved-path configuration, the initial simulations indicated stress values exceeding the yield strength of Aluminium Alloy 2024-T6 near the intersection region.

This behaviour was attributed mainly to concentrated numerical constraints applied to individual nodes.

To overcome this limitation, a distributed multi-node constraint strategy was introduced.

The modified model considers several neighbouring nodes around the intersection region, reducing artificial stress peaks.

The modified approach produced a smoother stress distribution and better represented the expected physical behaviour.

This confirms that for complex curved folding systems, constraint definition should be considered an essential modelling parameter rather than only a simulation setup step.

For the simulation, the same models and the same parameters were used, changing only the constraint in the nodes.

3.2.1 Results for displacement

Table 5 summarizes the maximum and minimum displacements resulting from the Altair HyperMesh folding simulations for each chosen configuration and thickness.

Table 5. Maximum displacement obtained from Altair HyperMesh simulations

Configuration	Thickness [mm]	Displacement min [mm]	Displacement max [mm]
	0.5	1.975E-03	1.777E-02
	0.7	1.946E-03	1.751E-02
	1	1.966E-03	1.770E-02
	1.5	1.991E-03	1.792E-02
	2 (Fig. 11)	2.083E-03	1.875E-02
	0.5	3.593E-03	3.735E-02
	0.7	2.846E-03	2.562E-02
	1	3.398E-03	3.058E-02
	1.5	2.693E-03	2.424E-02
	2 (Fig. 12)	3.481E-03	3.133E-02
	0.5	1.811E-03	1.630E-02
	0.7	1.798E-03	1.618E-02
	1	1.875E-03	1.687E-02
	1.5	1.849E-03	1.664E-02
	2 (Fig. 13)	2.331E-03	2.098E-02

The displacement maps are presented in Figures 11–13.

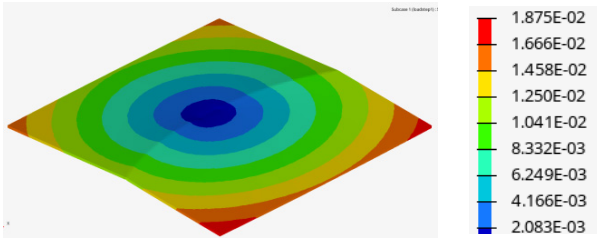


Figure 11. Displacement distribution for configuration C1, t = 2 mm

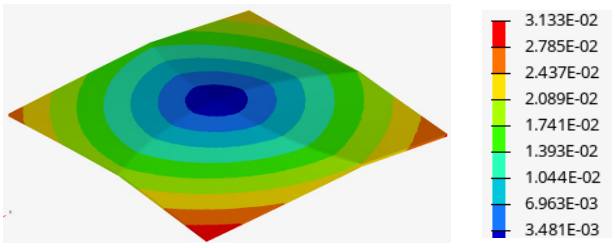


Figure 12. Displacement distribution for configuration C2, t = 2 mm

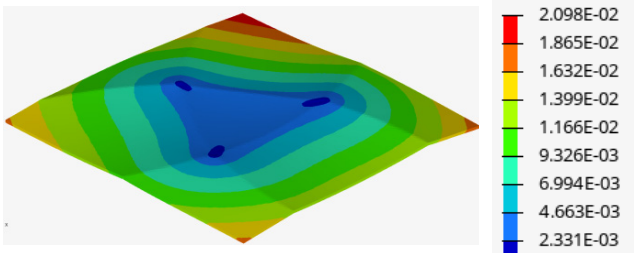


Figure 13. Displacement distribution for configuration C3, t = 2 mm

It can be concluded that the displacement is constant with respect to the thickness because the pressure applied to the edge multiplies the total force in exactly the same proportion as the stiffness of the section increases. On the other hand, the influence of the geometry determined by the number of curves depends directly on the positioning of the embedment. It can be seen that in the case of configuration two the displacement is maximum because the restriction at a single intersection point leaves the four subplans free to bend under the lateral pressure.

3.2.2 Von Mises equivalent stress analysis

Based on Altair HyperMesh simulations of the folding processes, Table 6 details the maximum and minimum Von Mises stress values across the selected configu–rations and thicknesses.

Table 6. Maximum Von Mises obtained from Altair HyperMesh simulations

Configuration	Thickness [mm]	Von Mises min [MPa]	Von Mises max [MPa]
	0.5	2.997E+00	2.697E+01
	0.7	5.806E+00	2.025E+01
	1	5.226E+00	2.271E+01
	1.5	3.016E+00	2.714E+01
	2 (Fig. 14)	4.853E+00	2.082E+01
	0.5	1.174E+00	1.057E+01
	0.7	2.075E+00	1.868E+01
	1	2.163E+00	1.947E+01
	1.5	1.929E+00	1.736E+01
	2 (Fig. 15)	2.035E+00	1.831E+01
	0.5	2.820E+01	2.538E+02
	0.7	1.540E+01	1.386E+02
	1	1.275E+01	1.148E+02
	1.5	1.185E+01	1.067E+02
	2 (Fig. 16)	9.521E+00	8.569E+01

The Von Mises equivalent stress maps are presented in Figures 14–16.

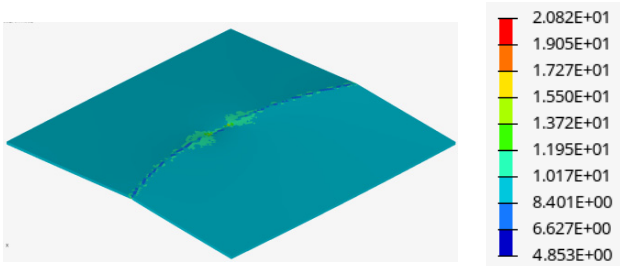


Figure 14. Von Mises stress distribution for configuration C1, t = 2 mm

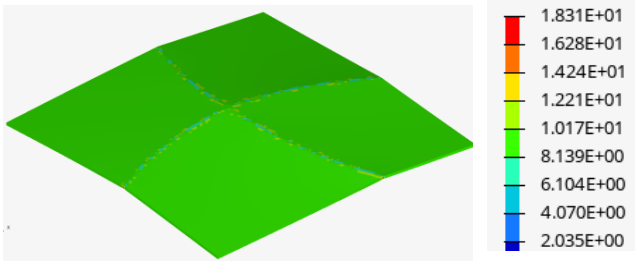


Figure 15. Von Mises stress distribution for configuration C2, t = 2 mm

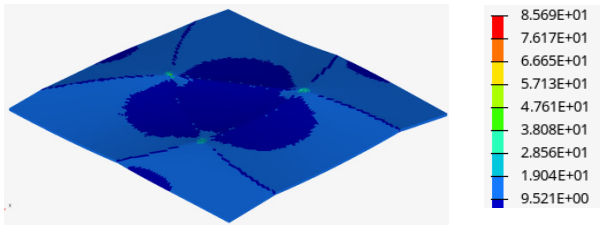


Figure 16. Von Mises stress distribution for configuration C3, t = 2 mm

From the data of the Von Mises max equivalent stresses, differences are observed between the fluc–tuations of the values depending on the number of curves. For configurations 1 and 2, the values of the equivalent stresses fluctuate rhythmically, the stress does not decrease continuously with the thickness, but varies slightly around 20 MPa and 18 MPa, res–pectively. This has the physical explanation due to the pure compression stress that appears in the plane. The structure is anchored at a single point for both configuration 2 and configuration 1. The metal sheet can deform freely under pressure on the sides, without generating large bending moments between the sup–ports. For configuration 3, a decrease in the stress value from 253.8 MPa (at 0.5 mm) to 85.69 MPa (at 2 mm) is observed. This is due to the fact that it can be considered a hyperstatic system with 3 points of con–straint, the material between these supports is prevented from moving freely. This creates huge internal reactions and local bending/shear effects between the fixed po–ints, increasing the thickness (t) increases the resistant section, which drastically reduces the maximum Von Mises stress.

- **Influence of boundary conditions**

The second numerical investigation focused on the influence of constraint definition.

The comparison between fully constrained curves and localized constraints revealed significant diffe–rences in deformation behaviour.

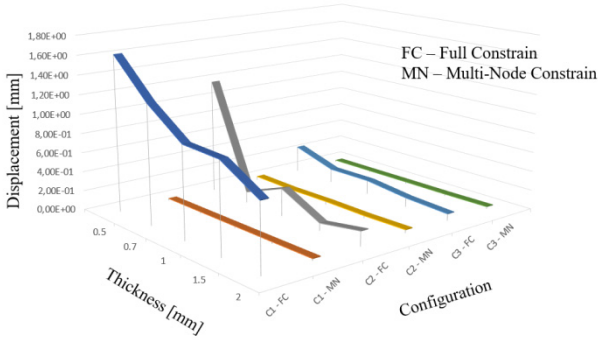
When the entire curved path was constrained, the structure exhibited artificially restricted deformation.

This condition produced:

- lower displacement values;
- increased local stress concentration;
- less realistic deformation patterns.

When only characteristic points were constrained, the sheet was able to develop a deformation mode closer to the physical folding mechanism.

The results demonstrate that boundary conditions represent one of the most influential modelling para–meters in numerical analysis of curved folded structures.



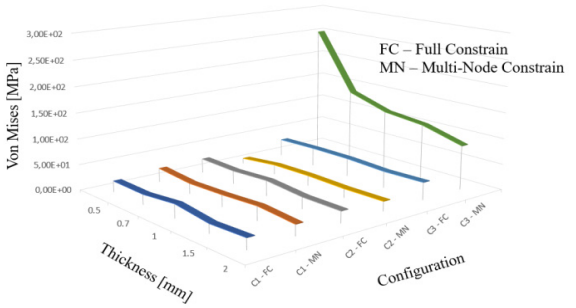


Figure 14. Variation of displacements for the two approaches: with full constraints (FC) and distributed constraint on multiple nodes (MN)

Incorrect constraint definition may lead to unrealistic stress predictions, particularly in regions where several folding paths intersect.

4. DISCUSSION OF RESEARCH CONTRIBUTION

The main scientific contribution of this study is the systematic comparison of different curved folding path topologies under identical mechanical conditions.

Previous studies have investigated curved folding mainly from geometrical and kinematic perspectives [3–7], while sheet metal simulations have generally focused on conventional forming operations [8,10,14,16].

The present research connects these two fields by demonstrating quantitatively how the number of curved folding paths modifies:

- structural stiffness;
- deformation distribution;
- stress concentration;
- sensitivity to boundary conditions.

The obtained results show that curved folding topology can be considered an additional structural design parameter for developing lightweight free-form sheet structures.

5. CONCLUSIONS

This study investigated the influence of curved folding path topology on the mechanical behaviour of thin aluminium sheet structures through numerical simulation. Three different free-form folded configurations were analysed, consisting of one, two, and three intersecting curved folding paths, under identical geometrical, material, and loading conditions.

The main conclusions obtained from this research are the following:

1. Curved folding topology has a significant influence on the structural stiffness of thin sheet structures.

The increase in the number of curved folding paths resulted in a considerable reduction of maximum displacement. The three-curved-path configuration exhibited the lowest deformation values due to the subdivision of the sheet into multiple deformation regions and the increase of geometric stiffness.

The results demonstrate that curved folding paths can act as passive stiffening elements without increasing material thickness.

2. Increasing the number of curved folding paths produces a simultaneous increase in stiffness and local stress concentration.

Although additional curved paths reduce global deformation, the interaction between multiple deformation zones generates higher Von Mises equivalent stresses, especially near intersection regions.

Therefore, curved folding design requires a balance between stiffness improvement and stress concentration control.

3. Sheet thickness strongly affects the deformation response of folded structures.

Increasing the aluminium sheet thickness from 0.5 mm to 2 mm significantly reduced displacement for all investigated configurations.

However, thickness variation alone cannot eliminate stress concentration effects generated by complex curved folding geometries.

4. Boundary condition definition represents a critical parameter in numerical modelling of curved folded sheets.

The comparison between fully constrained folding paths and localized constraints demonstrated that constraint strategy strongly influences the predicted deformation mechanism.

Fully constrained models may generate artificially high stresses, while localized and distributed constraints provide a more realistic representation of curved folding behaviour.

5. The multi-node constraint approach improves the reliability of numerical predictions in critical regions.

For configurations containing three intersecting curved folding paths, concentrated point constraints generated unrealistic stress peaks.

The introduction of distributed constraints around the intersection area reduced numerical singularities and provided a smoother stress distribution.

6. The combined use of meshless and finite element simulation methods provides an efficient methodology for free-form folded structure analysis.

Altair SimSolid enables rapid evaluation of multiple design configurations during preliminary development stages, while Altair HyperMesh provides detailed information regarding local stress distribution and critical regions.

The integration of these approaches represents an effective strategy for analysing complex folded sheet structures.

The main contribution of this research consists of establishing a systematic numerical relationship between curved folding path topology and the mechanical response of thin metallic sheets.

Unlike previous studies focused mainly on geometric generation or kinematic behaviour of curved folding structures, this work provides a quantitative comparison of different curved folding configurations under identical mechanical conditions.

The obtained results can support the development of lightweight free-form structures for mechanical engineering, architectural applications, and customized manufacturing.

Future research directions Further investigations will focus on:

- experimental validation of numerical predic–tions;
- nonlinear elastic-plastic material behaviour;
- spring-back effects after forming;

- optimization of curved folding path geometry;
- manufacturing limitations and residual stresses;
- development of design guidelines for controlled generation of free-form surfaces.

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МОДЕЛИРАЊЕ И СИМУЛАЦИЈА ДЕФОРМАЦИЈЕ ЛИМА РАДИ ГЕНЕРИСАЊА САВИЈЕНИХ ПОВРШИНА

В. Корзану, А. Дуца, С.-М. Крецу, А. Корзану, М. Стојићевић

Структуре од слободно савијеног лима представљају нову класу лаких система код којих се геометријска деформација користи за трансформацију равних материјала у сложене тродимензионалне конфи–гурације. Иако су концепти закривљеног савијања опсежно истраживани са геометријског и кине–матског становишта, утицај топологије путање зак–ривљеног савијања на механички одговор металних лимова остаје недовољно квантификован. Ова сту–дија представља нумеричко истраживање пона–шања при деформацији алуминијумских лимова са различитим конфигурацијама путања закривљеног савијања. Анализиране су три геометријске конфи–гурације: појединачна путања закривљеног сави–јања, две укрштене путање закривљеног савијања и три укрштене путање закривљеног савијања. Евалуирано је пет дебљина лима под равномерним притиском на ивици у равни. Сви модели су развијени коришћењем параметарског CAD прис–тупа и анализирани под идентичним својствима материјала, геометријским димензијама и условима оптерећења како би се изоловао утицај топологије савијања. Утицаји дебљине лима и дефинисања гра–ничних услова истраживани су коришћењем комплементарних нумеричких приступа заснованих на софтверима Altair SimSolid и Altair HyperMesh. Резултати добијени за померања и Фон Мизесов (Von Mises) еквивалентни напон снажно зависе од укупне конфигурације и дебљине лима. Успостав–љени су математички регресиони модели да би се глобално померање и Фон Мизесов еквивалентни напон изразили као квадратне функције топологије савијања (C) и дебљине (t). Међутим, додатне укрштене путање савијања генеришу веће локалне

концентрације напона, посебно у областима где неколико механизама деформације делује интера–ктивно. Студија такође истиче важност дефинисања граничних услова у предвиђању понашања закрив–љених савијених структура при деформацији. Пот–пуно ограничене путање савијања могу увести веш–тачке концентрације напона, док локализована и расподељена ограничења пружају реалистичнији приказ физичког механизма деформације. Резултати успостављају систематску везу између топологије закривљеног савијања, крутости структуре, распо–деле напона и дефинисања ограничења. Предложена методологија може подржати пројектовање и опти–мизацију лаких структура од слободно савијеног лима за примене у машинству, архитектури и индустрији.