Simplified blank design methods of panel forming process

A-M. Yan

Open Engineering S.A. SAMTECH Group - 8 rue des Chasseurs Ardennais, 4031 Angleur, Belgium
URL: www.open-engineering.com *e-mail:am.yan@open-engineering.com*

ABSTRACT: This paper introduces simplified algorithms for predicting sheet configurations in panel forming production. Panel geometries are described using Non-Uniform Rational B-Splines technique. The blank design algorithms work conveniently in a non-dimensional parametric system. Two effective blank design approaches have been adopted and developed. The first method involves a simple geometric mapping based on the deformation compatibility condition, and the second approach performs minimization on the most-like even deformation corresponding to the lowest deformation energy, which, in an ideal situation, approaches well practical deformation path. Numerical applications show that combined use of these two methods allows to develop complex geometry in a low cost.

Key words: Sheet metal forming, blank design, surface development

1 INTRODUCTION

In developing a multi-point forming technique within a FP6 project DATAFORM, an important issue is to develop effective methods of blank design to determine the initial configuration of panels according to the designed shapes of panels. Strictly speaking, this calculation requires an inverse analysis of panel forming process, which is generally a difficult task even by finite element method, because some practical factors may be unknown in advance. Simple and effective analysis is significant for practical applications.

In this work, two direct methods of blank design were adopted. The first one involves a geometric mapping based on deformation compatibility condition. Although this method may be not very precise in the case of complex panels, its solution may provide good initial points to the second method of optimisation. The proposed optimisation mapping method is based on minimisation of even forming deformation. The objective function implied incompressibility condition in an implicit way. NURBS technique was used for geometrical description of panels. As a comparison, a similar approach by Cai etc [1] used finite element discritization for panel geometry and introduced explicitly the incompressibility as the constraint condition of optimisation. Specially, thickness variation data, when available, were introduced in the present methods to simulate better panel forming process. The developed two methods may be independently used. Otherwise, the solutions obtained by the first method may be used as good initial points for the second method of optimization. Numerical applications have been compared with finite element simulations to show efficiency of the methods.

2 BLANK DESIGN BASED ON GEOMETRICAL MAPPING AND DEFORMATION DATA

A pure geometric mapping method was presented in [2]. It is an approximate method for non developable surface. It considers only geometric condition but not any deforming mechanism of sheets during a practical forming process. Firstly, a 3D surface is divided into almost uniform grids. Then each grid is mapped to a plane with the following rules: 1) The area of each grid remains constant after mapping so that the total surface of the part keeps constant; 2) The surface of the blank keeps continuous. There are no cracks and overlaps; 3) The deformation is compliant with the assumption that the length of a pair of centre lines are unchanged and ledge lengths of grid change according to a proportional relation.

In the case of using NURBS technique, the surface is divided into 4 regions by centre point of $u=v=0.5$, Fig. 1. Taking the upper-right part as example, the calculation starts from the NURBS centre. The coordinates of grid nodes are determined, from left to right, from low to up, using the above three conditions. The detailed description is referred to [2].

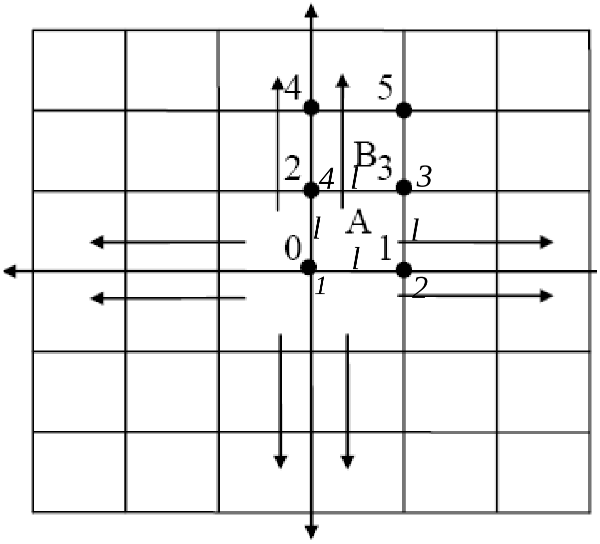


Fig. 1. Surface development process by geometric mapping

The above assumptions could not be generally satisfied in practice, leading to errors in the surface development. Some improvements or modifications may be considered:

1) If panel structures have not a pair symmetrical axis, the virtual centre lines are assumed corresponding to lines of u=0.5 and v=0.5. The points in these two lines remain on the lines when falling down from a space point to plane point without change in length of the virtual centre lines.

2) In most practical forming cases, deformation of sheets is not uniform depending on some practical factors. If the thickness data are available (by FE calculation or measurements), they may be used in geometrical mapping calculations. Starting from the incompressibility condition $s_i h_0 = \bar{s}_i \bar{h}_i$, we have an approximate relation of ledge length $l_j \sqrt{h_0} = \bar{l}_j \sqrt{\bar{h}_i}$, where the left term concerns the blank sheet data (area s_i, thickness h_0 and grid ledge length l_j) and the right term concerns designed shells. For more precise calculation it is necessary to consider strain variation in different directions, which will be discussed elsewhere.

3 BLANK DESIGN BASED ON MINIMISATION OF PANEL DEFORMATION

Define respectively the mesh points on the final surface and blank plate as $\bar{P}_i(\bar{x}_i, \bar{y}_i, \bar{z}_i)$ and $P_i(x_i, y_i, z_i)$. The length of two adjacent points (i,j) on the final surface and the bank sheet are:

$$\bar{l}_{ij} = \left|\overline{\bar{P}_i \bar{P}_j}\right| \quad \text{and} \quad l_{ij} = \left|\overline{P_i P_j}\right| \qquad (1)$$

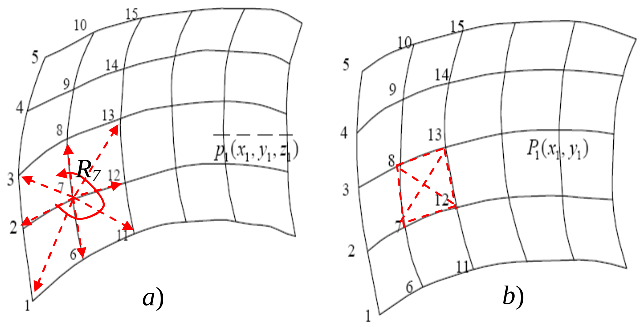


Fig. 2 Designed shell (left) and original flat sheet (right)

The method assumes that the actual forming process corresponds to most evenly distributed forming deformation requiring the smallest deformation energy. Therefore the problem may be formulated into a non-constraint optimization

$$\min : S = \frac{1}{2} \sum_{i}^{N} \sum_{j \in R_i} (l_{ij} - \rho_{ij} \bar{l}_{ij})^2 \qquad (2)$$

where N is the number of grid nodes; R_i is a node set around i-node as shown in Fig. 2a); ρ_{ij} is a weight factor having value close to 1, which measures the deformation along line l_{ij} and may be approximately related to the thickness variation. For a usual press forming process, one may consider that deformation in all direction may be about even. When thickness data of formed sheet is available ρ_{ij} may be estimated as $\rho_{ij} = \sqrt{\bar{h}_i / h_0}$ without considering the variation of strain in different directions. Ledge length l_{ij} is function of coordinates of node i and j such as $l_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$, $\bar{l}_{ij}$ depends only on given grid mesh and it may be calculated by geometrical integration. For convenience, we denote $\bar{l}_{ij}^0 = \rho_{ij} \bar{l}_{ij}$.

It may be verified that S in (2) represents the average of length difference square of corresponding ledges between final and initial sheets. The minimization condition is related to an ideal forming process with even deformation and requiring less energy. Although this process corresponds to the lowest energy principle, the ideal forming path may be modified by different contacting and boundary conditions, loading path, structural geometry and material properties. As a simplified method, these influencing factors are not considered in the present formulation and their effects are assumed small. It should also be stressed that although the incompressible condition of plastic deformation, is not explicitly represented in the above optimization formula, different to what done by Cai et al [1], this condition may be approximately satisfied by two facts: 1) when length of 6 ledge of any grid (see an element as example in Fig. 2b) are subject to constraint (2), the area of each grid, so the total surface of the sheet, change little; 2) the existing small area variation of each grid will be compensated practically by the variation of sheet thickness, which seems in agreement with real forming process. By consequence, this method may provide information of thickness variation due to forming process. The optimization conditions may be written as

$$\frac{\partial S}{\partial x_i} = \sum_{j\in R_i} (1-\frac{\bar{l}_{ij}^0}{l_{ij}})(x_i - x_j) = 0 \qquad (3a)$$

$$\frac{\partial S}{\partial y_i} = \sum_{j\in R_i} (1-\frac{\bar{l}_{ij}^0}{l_{ij}})(y_i - y_j) = 0 \qquad (3b)$$

They may be written in a vector form:

$$\mathbf{f} = \left[\frac{\partial S}{\partial x_1} \quad \cdots \quad \frac{\partial S}{\partial x_N} \quad \frac{\partial S}{\partial y_1} \quad \cdots \quad \frac{\partial S}{\partial y_N}\right]^T \qquad (4)$$

The second derivatives of objective function are:

- if $j=i$

$$g_{x_i x_i} = \frac{\partial^2 S}{\partial x_i^2} = \sum_{j\in R_i}\left[(1-\frac{\bar{l}_{ij}^0}{l_{ij}}) + (x_i - x_j)^2 \frac{\bar{l}_{ij}^0}{l_{ij}^3}\right]$$

$$g_{y_i y_i} = \frac{\partial^2 S}{\partial y_i^2} = \sum_{j\in R_i}\left[(1-\frac{\bar{l}_{ij}^0}{l_{ij}}) + (y_i - y_j)^2 \frac{\bar{l}_{ij}^0}{l_{ij}^3}\right]$$

$$g_{x_i y_i} = \frac{\partial^2 S}{\partial x_i \partial y_i} = g_{y_i x_i} = \frac{\partial^2 S}{\partial y_i \partial x_i} = \sum_{j\in R_i} (x_i - x_j)(y_i - y_j)\frac{\bar{l}_{ij}^0}{l_{ij}^3} \qquad (5a\text{-}c)$$

- if $j\in R_i$ (node set around node i)

$$g_{x_i x_j} = \frac{\partial^2 S}{\partial x_i \partial x_j} = -(1-\frac{\bar{l}_{ij}^0}{l_{ij}}) - (x_i - x_j)^2 \frac{\bar{l}_{ij}^0}{l_{ij}^3}$$

$$g_{y_i y_j} = \frac{\partial^2 S}{\partial y_i \partial y_j} = -(1-\frac{\bar{l}_{ij}^0}{l_{ij}}) - (y_i - y_j)^2 \frac{\bar{l}_{ij}^0}{l_{ij}^3}$$

$$g_{x_i y_j} = \frac{\partial^2 S}{\partial x_i \partial y_j} = \frac{\partial^2 S}{\partial y_i \partial x_j} = -(x_i - x_j)(y_i - y_j)\frac{\bar{l}_{ij}^0}{l_{ij}^3} \qquad (5d\text{-}f)$$

They constitute the Hansien matrix **G.** While **G** indicates decreasing deformation direction, **f** may be thought as residual vector and it is null when optimal solution **x** is found. So one has the following relation:

$$\mathbf{f}(\mathbf{x}+\Delta\mathbf{x}) = \mathbf{f}(\mathbf{x}) + \mathbf{G}(\mathbf{x})\Delta\mathbf{x} = 0 \qquad (6)$$

By an iterative process from initial solution $\mathbf{x_0}$, the iterative solution is:

$$\mathbf{x}_{k+1} = \mathbf{x}_k - \mathbf{f}(\mathbf{x}_k)\mathbf{G}^{-1}(\mathbf{x}_k) \qquad (7)$$

This is in fact Newton's iterative formula. The convergence condition may be one of the following two criteria.

$$\frac{\max(\mathbf{x}_{k+1} - \mathbf{x}_k)}{l_{ref}} < \varepsilon_X \qquad (8a)$$

$$\max(\mathbf{f}) < \varepsilon_f \qquad (8b)$$

where l_{ref} may be taken as nominal dimension of the sheet; ε_X and ε_f are two given small values.

Generally, this iterative process leads to a solution of blank design if it is convergent. However, the objective function (2) may be not an ideal concave surface so the solution may drop to local singular points that are not practical solution of the problem. As many similar problems, it is important to provide a good initial solution for a convergent optimization process. Two methods may be considered. The first one is to take coordinates (x, y) of spatial point of sheets as initial solutions. The second one is to take the solution of geometrical mapping. When optimal solutions are found, the thickness of each grid element may be calculated according to incompressibility condition. By comparing the predicted thickness variation with practical measurement, the blank design quality may be evaluated.

4 APPLICATION EXAMPLES

4.1 Cylindrical or spherical sheets (R=200)

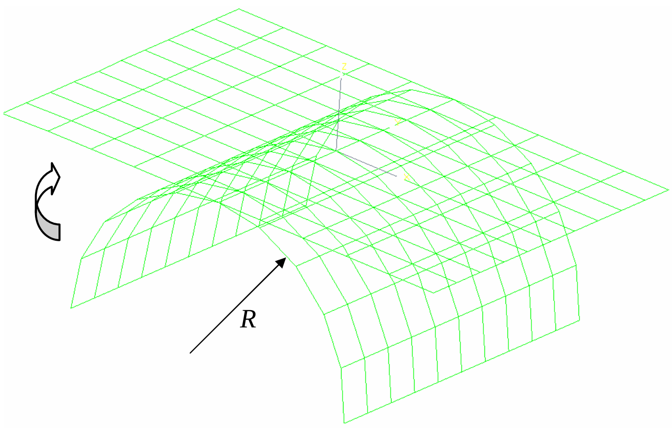


Fig 3 Blank design of a cylindrical sheet

In this simple example of cylindrical shell, both methods of geometrical mapping and optimization mapping lead to exact results: the developed surface is a rectangle plate. In the case of developing a spherical shell (the figure is not presented here), the difference between two methods is small. Specially, with very different grid meshes (one using 2×2, another 10×10) almost same results were obtained by using optimisation mapping method.

4.2 Saddle-shaped sheets

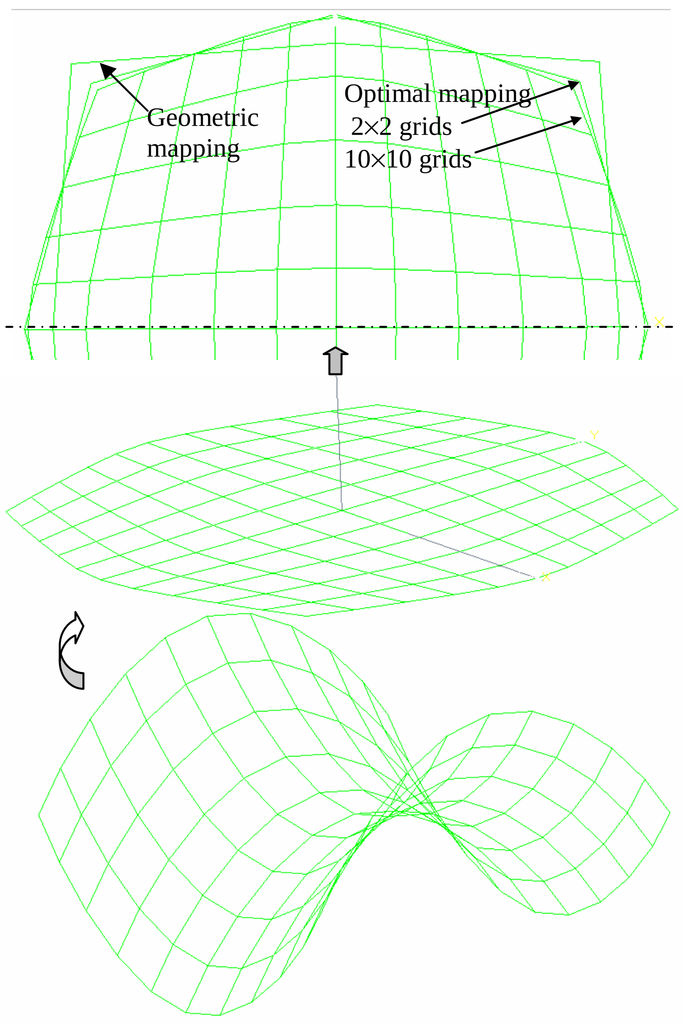
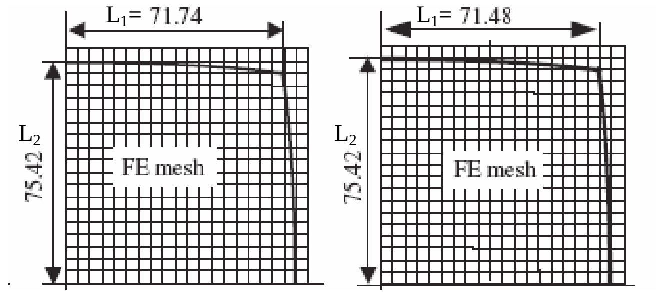


Fig 4 Blank design of a hyperbolic parabolic sheet

Now we consider a very deep saddle-shaped sheet ($z^2 = x^2/10^2 - y^2/10^2$, L_x=L_y=140). Since forming process involves very large deformation, it is a challenging task to develop this sheet. As shown in Fig. 4, there is not obvious difference between solutions with different meshes (grids). However, the results of two methods are quite different. Numerically, the geometric solution may be used as initial points for the optimization method, especially for a very deformed panel problem having convergence difficult.

In order to verify the precision of the presented methods, we compare the present results with a finite element simulation on a similar structure of two kinds of material ($z^2 = x^2/15^2 - y^2/15^2$), Fig. 5. Only two typical lengths L_1 and L_2 are compared with the present calculation in table 1, showing excellent agreement, even when very simple 2×2 mesh was adopted in the present calculations.



a) Steel 1010 b) Aluminium 2024-T351

Fig. 5 Finite element simulation results using ABAQUS [1]

Method	GeoMapping		OptiMapping		
mesh	2×2	10×10	2×2	10×10	20×20
L_1	73.84	73.66	**72.88**	**71.19**	71.08
L_2	74.29	74.29	**75.88**	**75.75**	75.70

Table 1 Numerical calculations of length L_1 & L_2

5 CONCLUSIONS

Simplified methods of blank design of panel forming process were developed, and verified by comparing to existing finite element solutions to shown their efficiency. The geometrical mapping method assumes symmetrical structure and considers only geometrical compatibility condition; it may give approximate solution for a general panel forming process. The developed optimisation mapping method assumes a deformation path with smallest evenly distributed deformation corresponding to the lowest deformation energy, which, in an ideal situation (not considering practical forming conditions), corresponds to most-like practical deformation path of a sheet forming process. A combined use of these two methods allows us to treat complex geometry in a low cost.

ACKNOWLEDGEMENTS

Researches were performed in DATAFORM project funded by the European Commission under the 6th Framework Programme in the area of Aeronautics (Contract N° 030877).

REFERENCES

1. Zhong-Yi Cai, Ming-Zhe Li, Hai-Ming Zhang, A simplified algorithm for planar development of 3D surface and its application in the blank design of sheet metal forming, *Finite Elements in Analysis and Design* **43** (2007), 301-310
2. Jilin University (Dieless Forming Technology Center), Technical Report for Multi-Point Forming, *DATAFORM project research report*, Dec. 2006