MODELING AND SIMULATION BASED ON INVERSE FINITE ELEMENT METHOD FOR UNFOLDING LARGE AND THICK BLADES OF FRANCIS TURBINES

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ABSTRACT

The metal pressing process is widely used in industries, such as energy, civil, automotive and shipbuilding engineering. For the design of the process, blank design is firstly performed to determine the dimension of the flat blank. Traditionally, the trial and error approach is used. However, this approach wastes much time and raw materials, especially in manufacturing the blades of large Francis turbines. The rapid development of the computing technology makes it possible to get optimum blanks by numerical modeling and simulations. In this paper, the multi-step inverse finite element approach is investigated for the blank design and an elasto-plastic model has been built using the well-known software ANSYS. Unfolding tests with simple geometries have been carried out and the numerical results agree well with the results obtained by analytical analyses. Finally, a large and thick blade of Francis turbines for hydropower plants has been successfully unfolded.

Keywords: finite element method, inverse approach, pressing forming, blade, blank design, Francis turbine

1. INTRODUCTION

A runner is one of the fundamental components of a Francis turbine for hydropower plants and the manufacturing of its blades using pressing process from a flat blank has many advantages (Casacci, Bosc, Moulin, and Sauron 1977; Casacci and Caillot 1983). This process is widely applied in other industries, such as automotive, shipbuilding and civil engineering. For the design of the process, firstly, blank design is performed to determine the dimension of the flat blank. Traditionally, the trial and error approach is used in blank design. However, this approach wastes much time and raw materials, especially in manufacturing the blades of large Francis turbines. Hydraulic conditions and cost of energy make design of Francis turbines very variable from site to site. Therefore the blade design is custom and not standard, the raw material trimmed away and the trimming time after the pressing process are very costly due to the over dimensioned blank to ensure the machining for the final shapes or the pressed blades. With the powerful development of the computing technology, numerical modeling and simulation are widely applied (Feng, Champliaud, and Dao 2009). Several methods were attempted to obtain the optimum blank, such as the slip line method (Kuwabara and Si 1997; Chen and Sowerby 1996), the roll-back method (Kim, Kim, and Huh 2000), the sensibility analysis method (Shim, Son, and Kim 2000), the initial velocity of boundary nodes methods (Son and Shim 2003) and the geometric mapping method (Blount and Stevens 1990; Ryu and Shin 2006). The most popular method is the inverse approach (IA) method. Some varieties of this method can be found in publication, such as the updated inverse approach (Zhang, Liu, and Du 2010); the one-step inverse approach with energy-based algorithm (Tang, Zhao Hagenah, and Lu 2007; Zhang, Hu, Lang, Guo, and Hu 2007), the multi-step inverse approach with membrane elements (Guo, Batoz, Detraux, and Duroux 1990; Lee and Huh 1998; Lan, Dong, and Li 2005; Nguyen and Bapanapalli 2009) and the multi-step inverse approach with shell elements to take consideration of bending effect (Guo, Batoz, Naceur, Bouabdallah, Mercier, and Barlet 2000; Lee and Cao 2001; Azaouzi, Belouettar, and Rauchs 2011).

There are so many papers involving in inverse finite element approach; however the data is not easily accessible. In this paper, the multi-step inverse approach is investigated through the well-known and easily accessible software ANSYS. The approach is applied to the blank design of large and thick blades of Francis turbines for hydropower plants. The flat blank is obtained from the desired blade which is the finally deformed shape of the pressing process.

2. FORMULATION

In inverse finite element approach, the initial state of the model is the deformed shape obtained in the pressing process and the final state is the flat blank. The given variables are the constant thickness and the geometry of the deformed shape and the unknowns are the thickness and the strain/stress of the flat blank, the coordinates of the flat blank in the working plane. Figure 1 shows the principle of the inverse approach, where the 3D deformed shape C passes to the 2D flat blank C^o. Each point P on C has an orthogonal projecting point P* on the working plane defined by the flat blank. The vertical displacement of point P is forced to be the distance between the two points P and P*. The process is characterized by geometry and material nonlinearities. The actions of the die and the punch are simplified by external forces. The principle of virtual work is established on the 3D deformed shape C as follows:

$$W = \sum_e W^e = \sum_e W_{int}^e - \sum_e W_{ext}^e = 0 \tag{1}$$

where the virtual internal work is given by

$$\sum_e W_{int}^e = \sum_e \int_{V^e} \varepsilon^{*T} \sigma dV \tag{2}$$

and the virtual external work is given by

$$\sum_e W_{ext}^e = \sum_e \int_{V^e} u^{*T} f dV \tag{3}$$

where ε^* and u^* denote the virtual strain and the virtual displacement, respectively. σ and f denote the Cauchy stress and the external forces which represent the tool actions, respectively. e denotes the sum of the elements. V_e denotes element volume.

Nonlinear equation (1) is solved by the following Newton-Raphson method (Ansys 2010):

$$[K_T^i]\{\Delta U\} = \{F_{ext}(U^i)\} - \{F_{int}(U^i)\} \tag{4}$$

$$[K_T^i] = \left[-\frac{\partial\{R(U)\}}{\partial\{U\}}\right] \tag{5}$$

$$\{U^{i+1}\} = \{U^i\} + \{\Delta U\} \tag{6}$$

where $[K_T^i]$ denotes the Jacobian matrix or the tangent matrix. i denotes the current iteration. $R(U)$ represents the residual vector. $\{F_{ext}(U^i)\}$ represents the vector for the external loads and $\{F_{int}(U^i)\}$ represents the vector for the internal loads. The solution $\{U^{i+1}\}$ contains the displacements of the projecting points of the nodes in the working plane which defines the flat blank.

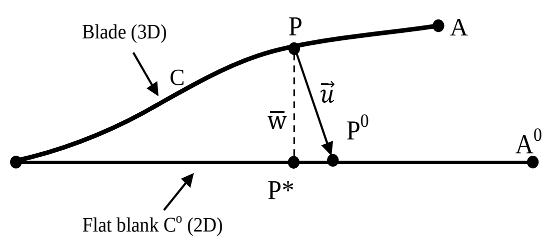


Figure 1: Schematic description of inverse approach

3. MODELING AND SIMULATIONS

The model represented by equation 1 is modeled with static analysis method under ANSYS environment. Inertial and damping effects, except of the static acceleration, are ignored.

3.1. Unfolding tests of Cylindrical Sections

Stainless steel was used in the models in this paper and the material properties (Table 1) were represented by a bilinear isotropic material model (Figure 2), where E denotes the elastic modulus, E_T denotes the tangent modulus, σ_Y denotes the yield stress. Elasto-plastic model with large displacement was established under ANSYS environment. 4-node shell elements were used to take account of the bending effect of thick blank. There was only one element with five integration points in the thickness direction. The nodes were located at the middle surface of the blank. Each node had six degrees of freedom (translations in the x, y, and z directions, and rotations about the x, y, and z axes).

Table 1: Material properties of stainless steel

Elastic modulus (GPa)	200
Yield stress (MPa)	754
Tangent modulus (GPa)	2.0
Poisson's ratio	0.3
Density (kg/m^3)	7850

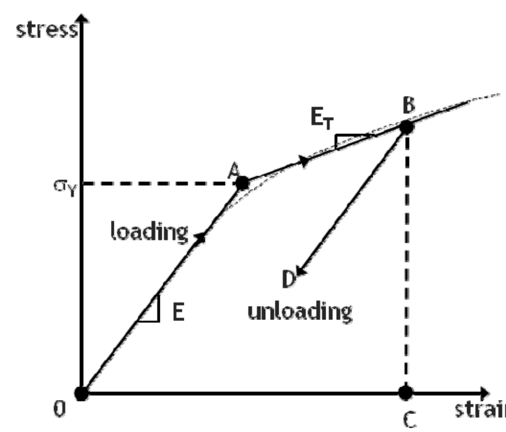


Figure 2: Bilinear material model

A cylindrical section meshed with shell elements for the unfolding tests is shown in Figure 3. In the figure, r was 1.5 m which was the radius of the middle surface of the cylindrical section. The width of the cylindrical section was 2 m and the thickness was 13 cm. In the tests, Angle θ was selected as 15^o, 30^o, 45^o, respectively. The models had the following boundary conditions: locked translation degrees of freedom in X, Y and Z directions for node 1, locked translation degrees of freedom Y and Z directions for node 2 and locked translation degree of freedom in Y direction for node 3, the other nodes had predefined displacements in Y direction. These predefined values were the distances of each node to the working plane for unfolded geometry or the flat blank which defined by nodes *1*, *2*, and *3*. The simulation gave the displacement of each node in *X* and *Z* directions in the working plane. As the motion of node *2* presented the motion of the free edge, the length of the cylindrical section *L* was determined by the following equation:

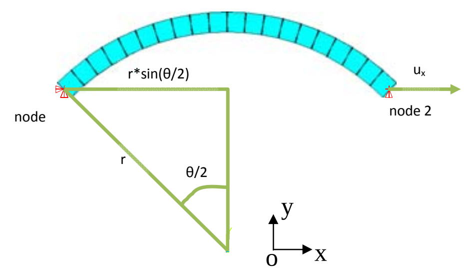
$$L = 2r \sin\frac{\theta}{2} + u_x \quad (7)$$

where u_x denotes the displacement of node *2* in *X* direction; *r* denotes the radius of the cylindrical section.

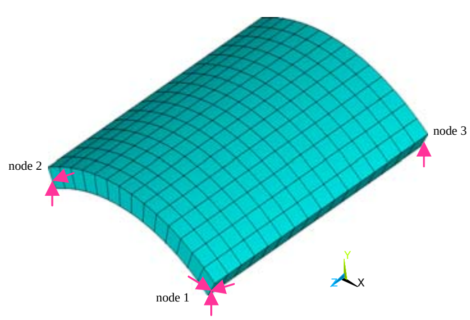
The theoretical length was calculated by the following equation:

$$L_{theoritical} = r\theta \quad (8)$$

In Table 2, the lengths obtained by the numerical simulations are compared with the values calculated by equation (8). The maximal error was 0.03% which indicated that the inverse approach gave satisfactory prediction of the flat blank.



(a)



(b)

Figure 3: Schematic description of inverse FE approach for a cylindrical section: (a) inverse FE model of a cylindrical section and its boundary conditions; (b) Geometrical setup for unfolding a cylindrical section

Table 2: Lengths of unfolded cylindrical sections compared with theoretical lengths

Angle θ (deg)	Theoretical length (m)	Length obtained by simulation (m)	Error (%)
30	0.7854	0.7853	-0.02
60	1.5708	1.5704	-0.02
90	2.3562	2.3556	-0.03

3.2. Unfolding of a Blade of Francis Turbine

The blades of large Francis turbines have complex geometries with different thicknesses and curvatures at different locations. This complex geometry is obtained by machining a pressed shape from pressing process. In such a process, a flat blank with constant thickness is firstly pressed to form a shape with little difference of thickness comparing to the flat blank. Then, the deformed shape is machined by a 5-axis CNC milling machine to obtain the desired curvature and thickness at each location of the blade (Sabourin, Paquet, Hazel, Cote, and Mongenot 2010).

During the unfolding of the blade with the inverse approach, it is supposed that the model for the unfolding of Francis turbine blades had also a constant thickness of 13 cm (Figure 4). At first, a working plane was defined by 3-point set: one point was located at the apex of the blade which coincided with the origin of the coordinate system, and two other points on the blade with reasonable distances from this apex (Figure 5). The material properties and element type were as the same as those used for the tests with simple geometries of the previous section. The unfolding procedure was also similar as the one used for the tests with simple geometries described in the same section. The boundary conditions were defined by the three points which defined a new coordinate system as follows: locked translation degrees of freedom in *X*, *Y* and *Z* directions for the point at the origin of the coordinate system (point *1*), locked translation degrees of freedom in *Y* and *Z* directions for the second point (point *2*), locked translation degree of freedom in *Z* direction for the third point (point *3*). The displacements of the other nodes in *Z* direction were predefined. These predefined values were the distances of each node to the working plane. For ensuring the computational convergence, multi-step approach was applied to divide the total predefined displacement of each node by the number of steps and a loop was used to compute the predefined displacements of each node.

The elasto-plastic model had a structural mesh with 1480 nodes and 1404 elements. A numerical simulation took about 96 seconds of CPU time. The middle surface of the flat blank obtained from the simulation had an area of 3.66 mm^2. The flat blank and a blade of Francis turbines presented in dotted mesh are shown in Figure 6. Figure 7 illustrates the Von Mise stress distribution of the flat blank. The maximal Von Mises stress was 1003 MPa which was located at the highly deformed zone where the blade had the maximal curvature (Figure 8). In this zone, the mechanical strain in the normal direction of the flat blank had the maximal value (Figure 9) which indicated that the maximal thickness change occurred in the zone with maximal curvature. However, the thickness changes at any location were very small. Taking consideration of the element of the maximal value in Figure 9, the distribution of total mechanical strain in thickness direction of the element with maximal value is illustrated in Figure 10. Since the deformation beside the middle surface had nearly equal values and opposite signs, therefore, the thickness change during the unfolding was neglected.

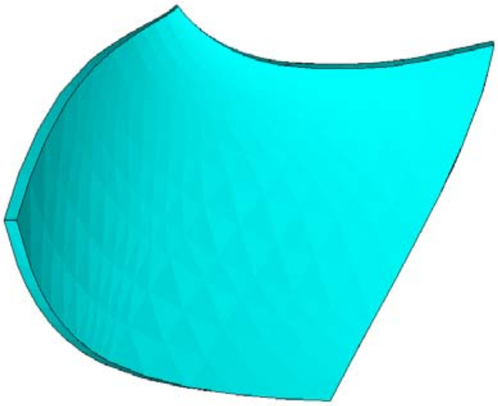


Figure 4: Geometry of Francis turbine blades

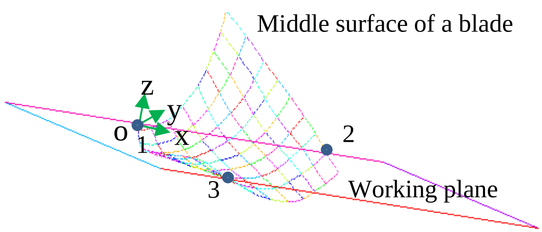
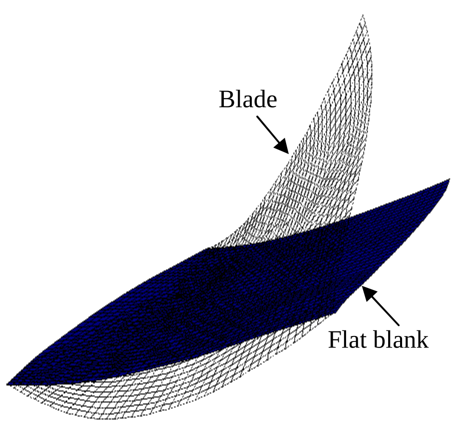


Figure 5: Middle surface of a blade of Francis turbine



(b)

Figure 6: Comparison between the flat blank and the blade

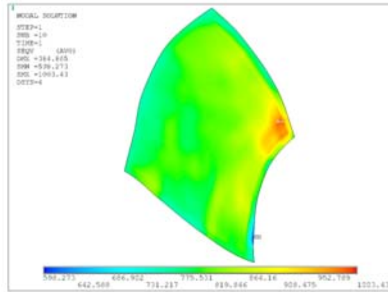


Figure 7: Von Mises stress distribution in the flat blank

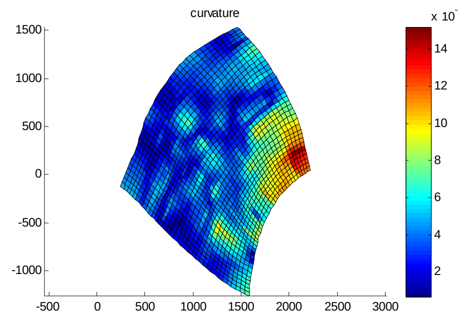


Figure 8: Distribution of residual stress of the flat blank compared with the curvature of the blade

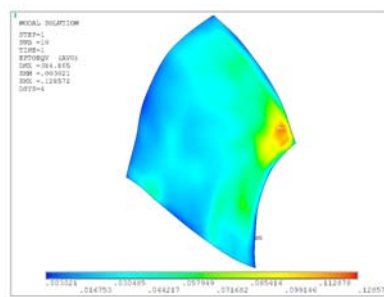


Figure 9: Von Mises total mechanical strain distribution in the flat blank

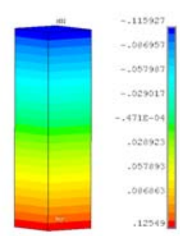


Figure 10: Distribution of total mechanical strain in thickness direction of the element with maximal value

CONCLUSIONS

Unfolded blank for thick and large blades of Francis turbine is obtained using finite element method under the easily accessible and common used software ANSYS environment. Unfolding tests with simple geometry with multi-step inverse approach are carried out and results shown that the error compared with analytical ones are less than 0.03%. The results show that the maximal thickness change occurred in the zone with maximal curvature. Future works will concentrate on adding automatically a minimum extra contour for machining purpose at the edges, on running simulations of the pressing process with the obtained blank to produce the desired blade and on validating the procedure with upcoming experiments.

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