An Efficient Implementation of Plasticity for Rollforming Simulations

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Rollforming is a continuous process in which the cross-section of sheet metal is bent incrementally by a number of roll stands along the axial direction x of the forming line to achieve a desired cross-sectional profile. The low thickness of the sheet justifies the use of the nonlinear *Kirchhoff-Love shell* theory with three translational and two rotational degrees of freedom [1]. We apply the finite element method and utilize a *Mixed-Eulerian-Lagrangian* (MEL) description [2] to decouple the downstream motion of the material particles along the forming line from the nodal deflections. Consequently, an advection term with the transport rate v emerges in the material time derivative $\dot{\square} = \partial_t \square + v \partial_x \square$. We seek the steady-state solution with a Newton-Raphson algorithm and employ an operator-split method to divide a time increment into a quasi-static phase and a transport phase to account for the motion of material particles. The quasi-static phase features the iterative solution of the balance equations and a predictor-corrector scheme to establish admissible elastic-plastic states; the transport is carried out with a first-order upwind scheme.

We employ a *stress-resultant plasticity* model [3], which operates directly on the 2D material surface of the shell and mimics the plastification through-the-thickness of the continuum with a *structural work hardening* law. Associative rules are introduced for the material rate of the plastic bending and membrane strains, $\dot{\mathbf{K}}_\mathrm{p}$ and $\dot{\mathbf{E}}_\mathrm{p}$, and the dissipative power $\dot{A}_\mathrm{p}$. The yield surface is not smooth and, thus, requires regularization or active-set strategies [4] for the return mapping. The subsequent transport of the plastic quantities $\boldsymbol{p} = \left\{\mathbf{K}_\mathrm{p}, \mathbf{E}_\mathrm{p}, A_\mathrm{p}\right\}$ creates a disbalance of the system after each increment. We mitigate this effect by applying a *stationary prediction* to provide a qualified guess of the upcoming step j by updating the previously obtained solution after the last increment $j-1$ with:

$$\tilde{\boldsymbol{p}}_{j-1} = \boldsymbol{p}_{j-1} + \frac{\boldsymbol{p}(t_{j-1}) - \boldsymbol{p}(t_{j-2})}{t_{j-1} - t_{j-2}} (t_i - t_{i-1}). \tag{1}$$

This estimate is self-improving as the solution gradually approaches the steady state, which results in an increasingly faster convergence of the scheme as the transient simulation progresses. Numerical studies demonstrate a substantial reduction of the computation time, making the stationary prediction a promising tool for the efficient simulation of large industrial models. We compare the results of the stress-resultant model against the established continuum-based treatment of plasticity with a corresponding thickness resolution of plastic states.

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