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Implicit finite element study of non-steady effects in cold roll forming

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Abstract: The ability of ABAQUS Standard to obtain a non-steady implicit solution to the problem of cold roll forming a channel section is investigated. A solution can be found with careful selection of parameters, but solutions are unacceptably slow for commercial use. The implicit solutions show buckling on the first pass that does not develop into an edge wave, in contrast to a published explicit solution. Faster solutions to steady rolling can be obtained using ALE models that permit convection of stress in the direction of rolling.

Keywords: roll forming, non-steady, finite element method

1 Introduction

Roll forming is a process whereby an initially flat strip of metal is formed into a tube or structural section by passing through a series of rolls. Profiles of rolls have been estimated by using testing and simplified analyses. For instance, analysis of the process by assuming the deformed shape of the sheet and predicting the strains corresponding to this shape, is available commercially [1,2] (COPRA and PROFIL). If too much deformation is attempted in any one set of rolls, problems can result such as edge waves associated with local plastic buckling. It is of interest to predict these situations. Finite strip methods have been used [2] with limited accuracy. Finite element analysis of roll forming processes has been performed by a number of researchers, and analysis is now available commercially. An analysis using a single layer of assumed-strain solid elements is available in COPRA FEA [1]. COPRA automatically prepares data for the MSC/MARC solver. The approach of COPRA FEA minimizes computation by modeling a limited length of the strip rolled, which is held in place at two roll-stands. PROFIL offers an interface to ABAQUS explicit [2]. Both explicit and implicit finite element approaches to modeling roll forming have been taken by researchers [3-7]. Analyses have been mainly Lagrangian. Lagrangian analysis is a slow process, not only due to tracking the history of deformation, but also due to ever-changing contact between the strip being formed and the rolls. Boman and Ponthot [8,9] have published an arbitrary Euler-Lagrange (ALE) approach for predicting steady roll forming, which allows material to flow through the mesh in the rolling direction. This avoids revising the contact conditions as much as in a purely Lagrangian analysis, as the mesh does not move in the direction of rolling. However, the approach in [8,9] does not simulate the correct history of loading, replacing it with a series of clamping deformations, occurring as rolls are successively brought into contact. A difficulty of ALE analysis is that finite element stress fields in elements do not provide a good estimate of the local gradient of stress, which is needed to calculate how stress diffuses through the mesh. Boman and Ponthot avoid this by means of a finite difference estimate comparing stresses at neighbouring Gauss points of adjacent elements. Recently, a Lagrangian explicit approach was taken by Tehrani et al [10] to modeling rolling the channel section investigated experimentally by Bhattacharya [11]. They found edge waves if the angle on the first set of rolls exceeded 40 degrees.

The present paper investigates this same problem using implicit finite element analysis with ABAQUS. It is found that this angle does indeed lead to local plastic buckling of the flange being formed, as the strip rolled passes through the second stand of rolls for the first time. This does not necessarily produce an edge wave however, as a simulation assuming symmetry predicts that the buckled section passes through the rolls and the process stabilizes, which confirms observations in practice by Bhattacharya [11]. The on-going oscillations in strain reported by Tehrani et al [10] may be more to do with spurious inertia effects; a result of mass-scaling in the explicit analysis. The implicit analysis described in this paper does however predict some oscillation in contact forces on the rolls. This is associated with a cyclic variation in the extent of plastic deformation around each roll stand. An analysis without assuming symmetry shows more sign of oscillation in residual strains along the flanges of the formed section. Misalignment can also be modelled with such an analysis.

An alternative approach to finding a faster solution to the steady roll forming problem may be to use a relaxation method to correct the deformed shape, starting from an assumed profile of the strip rolled. This is easier said than done, however. A difficulty with conventional elasto-plastic finite element analysis, is that any plastic deformation that is implied in an initial profile is accepted by such an algorithm - the solution depends on the initial state, even with use of a tangent elasto-plastic modulus. On the other hand, the formulation of a rigid-plastic finite element analysis does explicitly minimize plastic work, and a rigid-plastic analysis can be used as a relaxation method. Strictly, nodal velocities are found that minimize the rate of plastic work. These can be used to iteratively revise the shape of the deformed sheet being rolled. This approach has been applied to other metal forming problems since 1982 [12-17], and has been applied to roll forming by Hong et al [18]. Hong et al approach the problem in two stages, solving a generalized plane strain problem to determine the deformed cross-section at each roll stand, and then using these solutions as boundary conditions on a 3D rigid-plastic model of the sheet between roll stands. Some allowance for elasticity is possible in a rigid-plastic analysis. Strains found from updated nodal coordinates can be separated into elastic and plastic strains, using the radial-return algorithm. Where stresses are below yield, the rigid-plastic response can be replaced with an elastic response [19]. If this approach is combined with an ALE treatment where the material flows through the mesh, then a more efficient numerical method is possible. A relaxation approach has a fundamental problem, that a thin sheet is much more flexible out-of-plane. Hence the deformation assumed initially tends to be corrected by changing out-of-plane deflections, but in-plane strains – like the edge strain that could cause plastic buckling, are more reluctant to change from their initial values. If initial strains are too large, they may be relieved by spurious buckling, sending the solution on an incorrect path. Hence it is best if the initial condition of a relaxation solution underestimates the membrane strains, if not starting from zero strains.

2 ABAQUS models of roll forming

Many studies have used the experimental data for roll-forming a channel section of reference 11, as a simple case to validate the methods of analysis. The geometry of the rolls for bending the sheet through a 40 degree angle is shown in Figure 1. To investigate the transient behaviour as a sheet of mild steel is fed through first a 40 degree roll and then one or more 60 degree rolls, ABAQUS models have been set up that actually feed the strip through the rolls, with the rolls driving the strip. However, the rolls cannot drive the strip through until they have first made contact. To avoid this difficulty, two approaches have been taken. Firstly, for each stand, the lower roll of Figure 1 has been moved up to clamp onto the strip, in an initial step before rolling commences. Secondly, the strip has been pulled into the first set of already rotating rolls by imposing a velocity on its leading edge for the time needed for it to make adequate contact. The first of these approaches is taken in the following model that exploits symmetry and the second in the following full model.

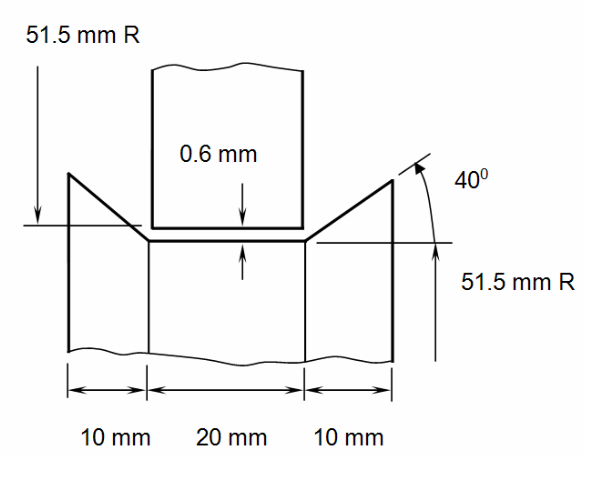

Figure 1 Geometry of the rolls (40^0 case)

Rolls were modeled as rigid bodies, and the strip being rolled was modeled with shell elements. Contact modeling required some care. ABAQUS provides a number of options for contact in implicit analysis. The augmented Lagrangian method of enforcing a normality constraint is available, but was found to have convergence problems applied to the roll forming problem. The alternative is a penalty method, which can have a linear or an exponential variation of normal contact force. The exponential approach, which provides soft contact initially, was found to work much better. Any of the approaches are likely to have difficulty if only one node is in contact, or if the normal to the contact surface rotates more than by a very small angle in one increment, or if the inter-penetration increases too much in one increment. The algorithm gives up on its contact search rather easily in fact. The contact modeling constrained what time interval could be used for simulation. The automatic adjustment of timestep size in the program was found to react too late to convergence difficulties to solve them, and needed assistance from the user, to stop it increasing the timestep too much. When simulating rolling, a timestep limit was set that implied that each element was only allowed to move about 1/5 of its length through the rolls in each update. On the other hand, simulating clamping the rolls onto the strip permits use of much larger timesteps, as contact conditions do not continually change. The automatic timestepping of ABAQUS works well on the clamping problem.

To improve the robustness of the contact calculations, by further softening the contact situation, one of each pair of rolls was mounted on a spring. This also reflects reality, as the actual roll and its mounting is not perfectly rigid. Coulomb friction with a coefficient of friction of 0.2 was used in the simulations.

3 Simulations conducted with ABAQUS

Tehrani et al correctly point out that the passage through the first roll stand stretches the flanges of a channel being formed more than the web, causing the strip to bend down until it encounters the second roll stand, when it is bent up again. The encounter with the second roll stand can lead to plastic buckling of the flange of the channel. A simulation with a half model and three roll stands of 40, 60 and 60 degree angles confirms that plastic buckling does indeed occur. The buckled section continues to move through the rolls, as shown in the screen snapshot of Figure 2. The plots of membrane edge strain of Figure 3, obtained from a simulation with two 40 degree roll stands, confirm this. Figure 3 shows the edge strain settling down to a steady value, with no evidence of an edge wave. This is in conflict with Tehrani et al, who show large oscillations in strain developing after the first roll. A possible explanation of the conflict is that the mass scaling used by Tehrani, while not causing the total kinetic energy to be a very large fraction of the energy, could have been enough to set off spurious dynamics. Explicit analysis is attractive as the contact problem becomes much more robust. The present author’s attempts at explicit analysis were found to be unsatisfactory due to similar mass-scaling problems, as it does not take much false mass added to a thin sheet to excite out-of-plane modes of vibration.

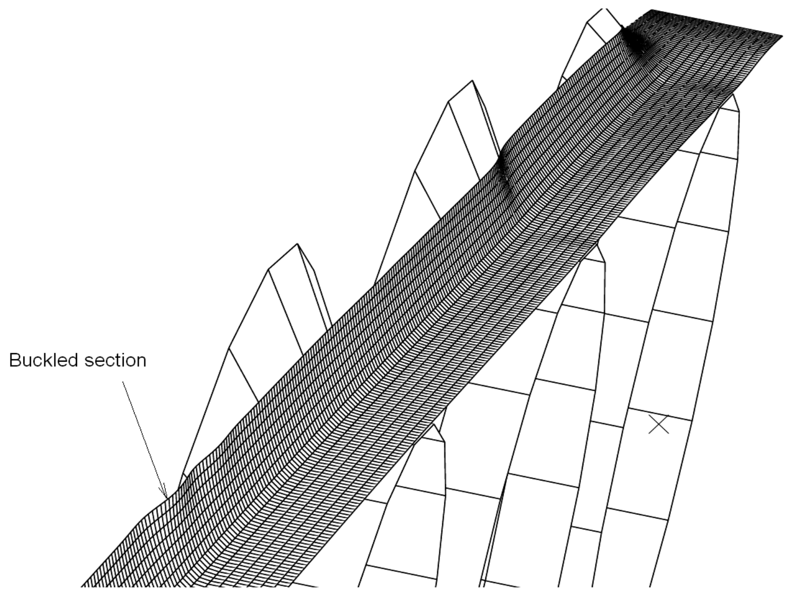

Figure 2 Deformed shape of a strip rolled for a half model of 3 stands (40^0, 40^0 and 60^0).

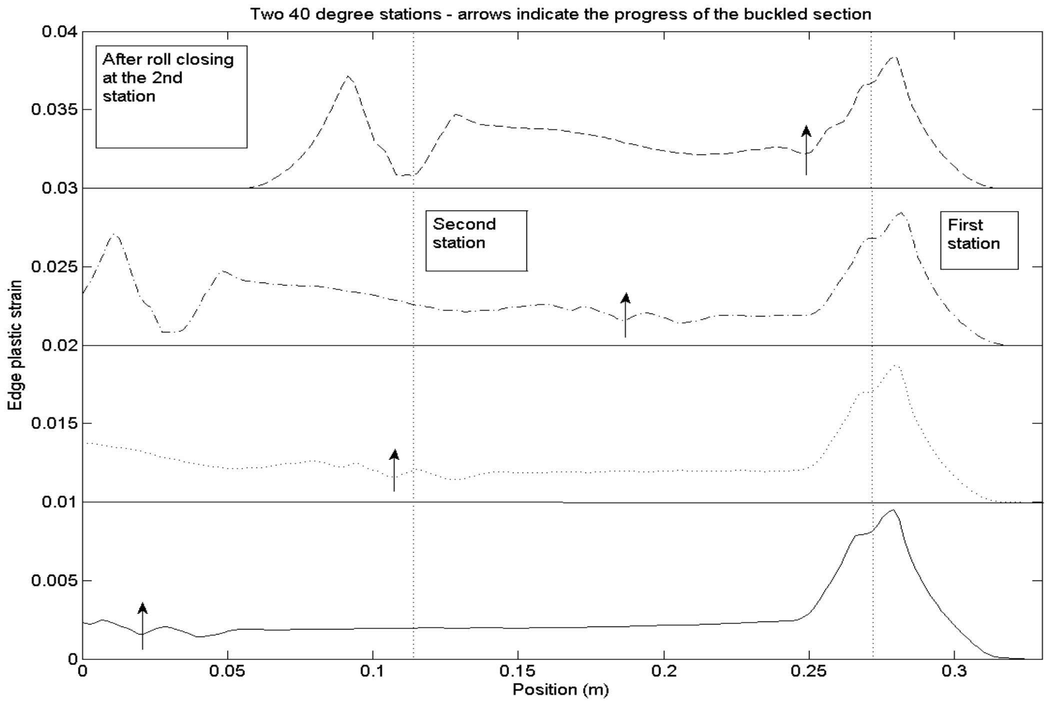

Figure 3. Distribution of strain along the edge of the strip rolled at four times, showing progress of buckled section.

An implicit simulation avoiding use of symmetry used the mesh shown in a deformed screen snapshot in Figure 4. The strain contours on the mesh reveal oscillation of edge strain. These could develop into an edge wave, if it became more severe. This model can represent the effect of misalignment. For instance, a sheet fed into the rolls displaced to one side does emerge twisted. The models also reveal the contact pressure distributions on the rolls, and hence give a guide to the prediction of roll wear.

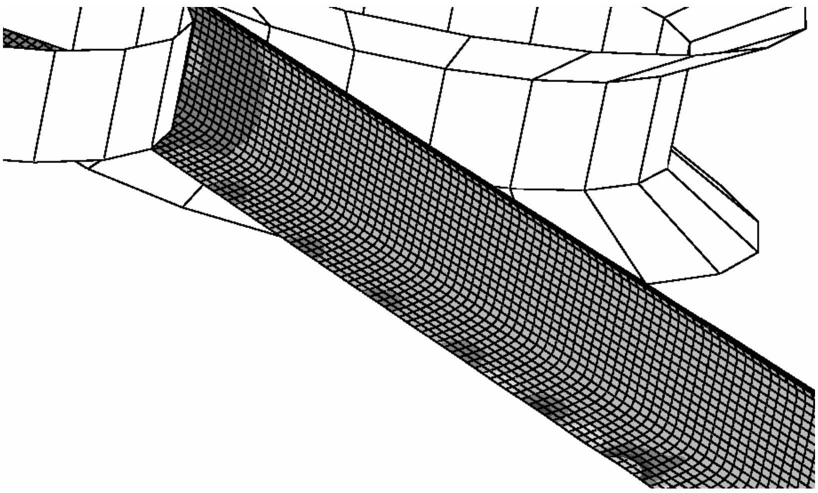

Figure 4. Full model of a channel section being rolled showing oscillation of edge strain.

4 Simulation by relaxation

Subsequent to the ABAQUS study, the problem of roll-forming a channel has also been investigated by finite element relaxation methods. An ALE approach is used: that is, the membrane stresses and bending moments are corrected each iteration for convection of stress through the mesh. While ABAQUS can do some implicit ALE simulations, the program only applies inflow/outflow boundary conditions for explicit analysis with solid elements. Hence the author's own software was used instead. To minimize computation a membrane model enhanced with bending terms based on the work of Yoo [16] was used. This model ignores membrane-bending coupling, and uses a preset elasto-plastic tangent modulus to describe bending. It has no rotation degrees of freedom, using a central difference of lateral displacements to estimate curvature. This model reduces computational time by an order of magnitude, but the accuracy suffers, as shown by the comparison of edge strain with ABAQUS Standard for 20 and 40 degree rolls, given in Figure 5. The mesh is a half model with 8 elements transversely by 108 elements longitudinally. The model starts with a guess of the deformed shape, of the sheet rolled, obtained by fitting a cubic transition in the direction of rolling, between two roll profiles, and a quadratic transition to the first roll-stand. It is first run with elastic membrane behaviour, correcting the error in equilibrium for 20 iterations. This obtains a much more realistic deformed shape of the sheet rolled, tending to lower the strains assumed initially. The material is then switched to rigid-plastic membrane behaviour at any Gauss point that exceeds yield, for further iterations. The resulting strains after 40 iterations are qualitatively similar to those of ABAQUS but stray too far negatively. This could be a problem with contact modeling, but also suggests that real shell elements, or assumed-strain solid elements, while less efficient, may be needed to get more acceptable answers. The ABAQUS solution may also be in error due to its soft modeling of contact. The relaxation solution, if fully converged, should lead to zero inter-penetration, as it uses constraint equations for normal contact. The relaxation solution ignores friction. A problem of the relaxation solution that has been observed is local buckling of the mesh at the rolls, in an unphysical manner. This can occur if the step size is too large.

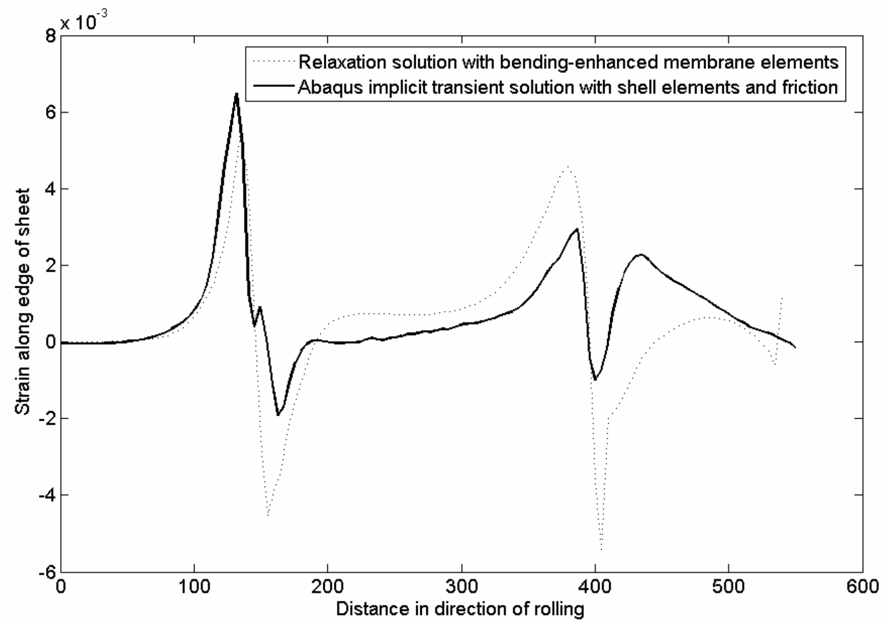

Figure 5. Comparison of transient implicit ABAQUS solution with a rigid-plastic ALE relaxation solution.

3 Conclusions and recommendations

There are a number of computational alternatives to modelling cold roll forming of a thin sheet. Both implicit and explicit approaches are available commercially, but explicit analysis can easily suffer from spurious inertia effects, and implicit analysis with ever-changing contact boundary conditions is very slow, and not robust. Implicit solutions obtained with ABAQUS revealed that non-steady effects in roll forming are mainly associated with feeding a sheet through the rolls the first time. Buckling that occurs on the first pass through the rolls may not continue once steady conditions of rolling are achieved. If only the steady solution is of interest, an ALE approach is attractive, but trials with a bending-enhanced membrane model show that converging successfully to the steady state is tricky and requires a very good initial guess of the deformed shape. While the stressing of a thin sheet is mainly due to membrane stress, a proper description of the nonlinear stress variation through the sheet thickness that accounts for both membrane and bending strains is needed for good accuracy.

References

[1] COPRA web page. DataM Software Engineering. www.roll-design.com

[2] PROFIL web page. UBECO Pty Ltd. www.ubeco.com

[3] Han, Z-W., Liu, C., Lu, W-P. and Ren, L-Q., Simulation of a multi-stand roll-forming process for thick channel section, Journal of Materials Processing Technology, 127(2002), 382-387.

[4] Heislitz, F., Livatyali, H., Ahmetoglu, M., Kinzel, G., Altan, T., Simulation of roll forming process with the 3_D FEM code PAM-STAMP, Journal of Materials Processing Technology 59(1996), 59-67.

[5] Alsamham, A., Hartely, P. and Pillinger, I., The computer simulation of cold roll-forming using FE methods and applied real time re-meshing techniques, Jiournal of Materials Processing Technology 142(2003), 102-111.

[6] Brunet, M. and Ronel, S., Finite element analysis of roll-forming of thin sheet metal, Journal of Material Processing Technology 45(1994), 255-260.

[7] Brunet, M., Mguil, S. and Pol, P., Modelling of a roll-forming process with a combined 2D and 3D FEM code, Journal of Material Processing Technology 80-81(1998), 213-219.

[8] Boman, R. and Ponthot, J-P., Finite element simulation of lubricated contact in rolling with the arbitrary Lagrangian-Eulerian formulation, Computer Methods in Applied Mechanics and Engineering 193(2004) 4323-4353.

[9] Boman, R, Papeleux, L., Bui, Q.V. and Ponthot, J.P., "A 3D arbitrary Lagrangian Eulerian approach for the numerical simulation of forming processes. Application to cold roll forming and metal cutting", III European Conference on Computational Mechanics: Solids, Structures and Coupled Problems in Engineering, Lisbon, Portugal, 5-8 June, 2006.

[10] Tehrani, M.S., Hartley, P., Moslemi Naeini, H. and Khademizadeh, H., "Localised edge buckling in cold roll-forming of symmetric channel section", Thin-walled Structures 44(2006), 184-196.

[11] Bhattacharya, D. and Smith, P.D., The development of longitudinal strain in cold roll forming and its influence on product straightness, advanced Technology of Plasticity, 191984), 422-427..

[12] Osakada, K. , Nakano, J. and Mori, K., Finite element method for rigid-plastic analysis of metal forming – formulation for finite deformation, International Journal of Mechanical Science, 24(1982), 459-468.

[13] Oh, S.I., Finite element analysis of metal forming processes with arbitrarily shaped dies, International Journal of Mechanical Science, 24(1982), 479-493.

[14] Mori, K., Osakada, K. and Oda, T., Simulation of plane-strain rolling by the rigid-plastic finite element method, International Journal of Mechanical Science, 24(1982), 519-527.

[15] Yang, D.Y., Chung, W.J. and Shim, H.B., Rigid-plastic finite element analysis of sheet metal forming processes with initial guess generation, International Journal of Mechanical Engineering Sciences, 32(1990), 687-708.

[15] Song, I.S., Shim, H.B. and Yang, D.Y., Rigid-plastic finite element analysis of sheet metal forming processes using a selective membrane/shell formulation, Journal of Materials Processing Technology, 47(1995),323-344.

[16] Yoo, D.J., Song, I.S., Yang, D.Y. and Lee, J.H.,Rigid-plastic finite element analysis of sheet metal forming processes using continuous contact treatment and membrane elements incorporating bending effects, 36(1994), 513-546.

[17] Hong, S., Lee, S., Kim, N., A parametric study on forming length in roll forming, journal of Material Processing Technology 113(2001), 774-778.

[18] Mori, K., Wang, U. and Osakada, K., Inclusion of elastic deformation in rigid-plastic finite element analysis, International Journal of Mechanical Engineering Sciences, 38(1996), 621-631.