MODELLING ROLL STACK DEFORMATION FOR FLAT ROLLING MILLS VIA FINITE ELEMENT METHOD: A CRITICAL REVIEW OF SOME SIMPLIFYING ASSUMPTIONS*

Yukio Shigaki[1]
Pierre Montmitonnet [2]
Jonatas Mezêncio Silva[3]

Abstract

A precise roll stack deformation model of a flat rolling mill is crucial for strip profile assessment as it depends strongly on the roll's deformation. The need for more and more advanced products with stringent both geometrical and mechanical tolerances (e.g., Advanced High Strength Steels – AHSS), with thinner and harder steel strips, demands more advanced simulation models. The present paper addresses assumptions made in Finite Element Method (FEM)-based roll stack models on some important, yet barely discussed features: What is the impact on precision of the simplifications such as symmetry and anti-symmetry? Should roll neck boundary conditions in bearings be considered as fixed or simply supported? In this paper a hybrid model developed by the authors for a general flat rolling mill is used to assess those questions. This model runs much faster (100x in some cases) than a whole-FEM-modeled 6-high rolling mill with the elastoplastic strip deformation, thanks to its simplifications adopted. This model assumes a steady state rolling condition, and the roll stack is modeled with tridimensional finite elements, and the loads are calculated via a slab method adopting a plane strain state for the strip deformation (especially true for thin strips). An industrial 6-high cold rolling mill is modeled and results on the application of symmetries and different boundary conditions on the roll's necks are presented. It is concluded that the application of symmetries and anti-symmetries for the 6-high rolling mill is possible for thin strips. And the way the necks are modeled does not impact on the final strip shape, though it influences the magnitude of the roll's displacement. The coupling of the strip with the work roll applied assuming a symmetry plane of the arc of contact has little influence on the strip shape.

Keywords: Flat rolling; Roll stack deformation; Strip profile; Finite element method

[1] *Naval engineer, D.Sc. in Metallurgy engineering (UFMG), Associate professor, Mechanical Engineering Department, CEFET-MG, Belo Horizonte, Minas Gerais, Brazil.* ***ABM Member****.*
[2] *Mechanical & Materials Engineer, PhD, Dr ès-Sciences Phys., Research Director, CEMEF, MINES ParisTech – PSL*, CNRS UMR 7635, Sophia Antipolis, France.*
[3] *Mechanical engineer, CEFET-MG, Belo Horizonte, Minas Gerais, Brazil.*

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1 INTRODUCTION

Cold rolled strips are widely used worldwide and the stringent requirements regarding mechanical properties and finishing quality demands high technology from rolling companies.

One of the most important parameters of a strip is its cross-sectional profile, being defined by differences in thickness along some points in transversal position. It is known that the flatness of a strip is highly dependent on the way its cross section deforms in each pass. Rolling mills have evolved too in answer, regarding stand design (Continuously Variable Crown CVC, 6-high stands, Fig. 1, etc.) or sensors and control systems. The latter require modelling of roll stacks of growing complexity.

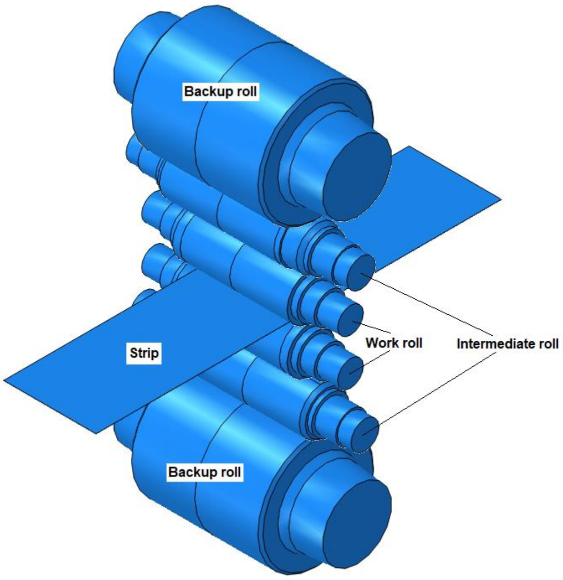


Figure 1. 6-high rolling mill.

In order to achieve a good control system over strip profile in a flat rolling mill, precise mathematical models are necessary. The more complex it becomes with the trend for thinner and harder strips (AHSS, for instance), still a challenging factor for many researchers.

As the strip profile depends strongly on the deformation of the roll in contact, it is imperative to develop an accurate model for the roll stack deformation.

Many researchers developed roll stack models for different rolling mills. Emicke and Lucas [1], Stone and Gray [2], Shohet and Townsend [3], and more recent works on flat rolling mill simulation based on the finite element method (FEM) were developed in order to calculate the strip profile [4,5]. The present paper addresses assumptions made in FEM-based roll stack models on some important, yet barely discussed features:

• what is the impact on precision of the simplifications such as symmetry and anti-symmetry?

• should roll neck boundary conditions (BC) in bearings be considered as fixed or simply supported?

Linghu [5] developed a 3D FEM analysis of strip shape in a 6-High CVC cold rolling mill. There are no details on the BCs for the roll necks. Through the same figure can be seen what looks like rigid connections resembling rigid bearings for the necks.

Kim, Lee and Hwang [6] present a full FE-based approach (strip FEM / roll stack FEM) for prediction of strip profile in flat rolling, sometimes adopting symmetry planes. Du et al. [7] developed a full FEM model of strip profile calculation in a 6-High cold rolling mill. They don't detail the BCs of the model, and by the figures it is possible to see the modeling of whole necks. Ginzburg [8] presented a 3D FE model based on spring and beam elements. He estimates the material and housing stiffness and adopts springs for the stiffness of the necks and bearings.

None of them analyze explicitly the boundary condition assumed for the roll necks in their finite element models.

In this paper a hybrid model developed by the authors for a general flat rolling mill is used to assess those questions. This model runs much faster (100x in some cases) than a whole-FEM-modeled 6-high rolling mill with the elastoplastic strip deformation, thanks to its simplifications adopted. This model assumes a steady state rolling condition, and the roll stack is modeled with tridimensional finite elements, the loads being calculated by a slab method adopting a plane strain state for the strip deformation (especially true for thin cold rolled strips). An industrial 6-high cold rolling mill is modeled and results on the application of symmetries and different boundary conditions on the roll necks are presented.

2 3D FE/MULTI-SLAB MODEL

2.1 FE hybrid model

Most modern flat rolling mills have multiple control devices for producing the required strip crown with minimum flatness defects. Rolls may be grinded with some polynomial shaped surfaces, use actuators on the roll chocks to provide roll bending, be displaced axially for better controlling the strip's edge drop and wear, etc.
The model presented here was developed in order to capture with the highest accuracy three-dimensional roll stack deformation, no matter its complexity.
In order to balance accuracy of results and computer time processing, some assumptions on roll stack symmetry are adopted, and for boundary conditions for roll neck bearing, as well.
The application of symmetry and anti-symmetry planes in the 3D FE model allows to run faster without compromising precision.
The strip profile is calculated from the roll stack deformation due to the rolling load applied. This load is calculated using a multi-slab method, Bland-Ford method with Hitchcock's roll flattening correction, or a more advanced roll loading calculation method (e.g. Noncirc [9]) for harder and thinner strips.
The model is iterative, and usually has a fast convergence, finishing within 6 to 10 iterations in the cases presented. More details may be found in [10].

2.2 Symmetry planes assumptions

The simulation of a flat rolling mill modelled with 3D FEM/Multi-slab method adopts some simplifications assuming symmetry and anti-symmetry planes to calculate the deformation of the rolls. Figure 2 shows those planes for a 6-high rolling mill.

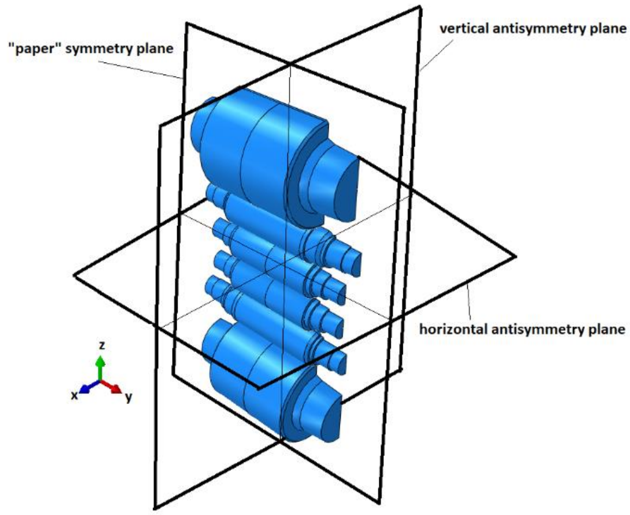
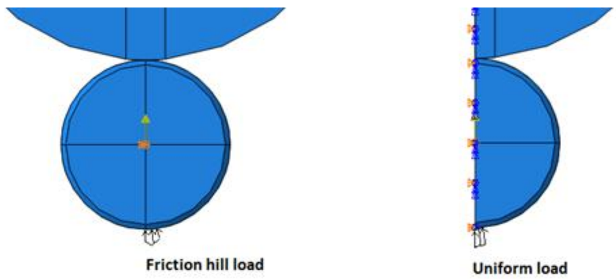


Figure 2. Simplification symmetry/anti-symmetry planes.

2.2.1 Paper symmetry plane

The paper symmetry plane assumes that both mill geometry and the normal pressure load in the arc of contact are symmetric to that plane. This includes an upstream/downstream symmetry hypothesis for the rolling load, according to Fig. 3.In order to understand the deformation behavior of the work roll in this case, a full model was developed (Fig. 3A) where the asymmetric "friction hill" rolling load is applied, and the simplified model, currently used in our model (Fig. 3B), was modeled with a uniform load with a total resultant load equivalent to the full model.



Case A Case B

Figure 3. Full model (A) and simplified model (B).

The industrial 4-high mill modelled has a 3μm camber with a parabolic shape.
For both models two cases were studied, one with roll bending forces applied, and the other not.

2.2.2 Vertical and horizontal (anti)-symmetry plane

When we isolate the strip and consider it as a free body in equilibrium, it is necessary that the resultant load vanishes, and this is accomplished when the pressure load on the top surface of the strip is identical to the pressure on the bottom surface. If a 4-high rolling mill is being modelled, this is not an issue, unless the strip has wedge, breaking the symmetry. In the case of a 6-high rolling mill in which we apply anti-symmetries, the deformed strip does not stay completely horizontal, and this can be questioned as a source for a difference on the top and bottom pressure profiles compensated eventually by peaks on the edges. In order to evaluate this problem, a whole 6-high rolling mill "indenting" a 2 mm thick strip is analyzed. This allows calculating the strip and roll displacement and the contact pressures over the strip and have an idea of its distortion and its influence on the equilibrium of the roll stack.

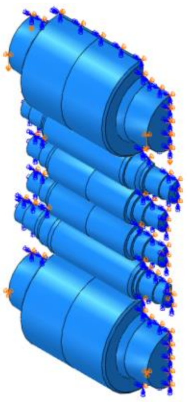


Figure 4. 6-high rolling mill model and boundary conditions applied.

To do that the whole 6-high rolling mill was modelled, top and bottom rolls (half) (see Fig. 4), and simply imposed a -0.5 mm vertical displacement on the top BUR (on its necks). It is an approximation only to assess that hypothesis. Bottom BUR necks are clamped and the strip thickness is 2 mm and 979.8 mm in width.

2.3 Roll neck boundary conditions

When rolls are modelled with FEM, their necks and respective boundary conditions influence on the results of the roll stack deformation. In order to check this influence, six roll neck models were simulated under the same uniform load for a 4-high rolling mill. The strip profile was, then, assessed.
A Morgoil type bearing for the backup roll necks are considered (Fig. 5).

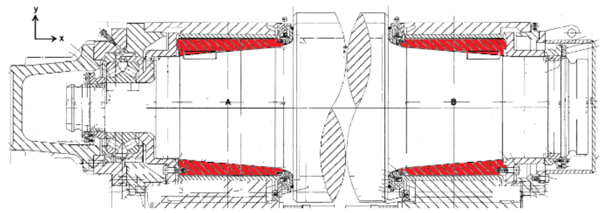


Figure 5. Schematic of Morgoil bearing system and backup roll necks.

The six cases considered are (see Fig. 6):

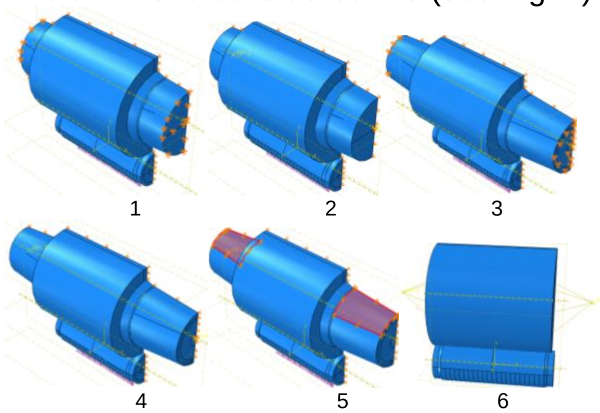


Figure 6. Six cases considered for boundary conditions for the necks.

Case 1 – Half neck modelled, vertical faces fixed (see Fig. 6.1)
Case 2 – Half neck modelled, vertical faces pinned (See Fig. 6.2)

Case 3 – Whole neck modelled, fixed (see Fig. 6.3)
Case 4 – Whole neck modelled, pinned (see Fig. 6.4)
Case 5 – Whole neck modelled, part of the top surface fixed (see Fig. 6.5)
Case 6 – No neck modelled, medium point of the neck pinned with couplings (see Fig. 6.6)
A 2 MN uniform vertical load is applied on the upper work roll for all cases. The FE mesh of Case 5, for instance, is shown in Figure 7.

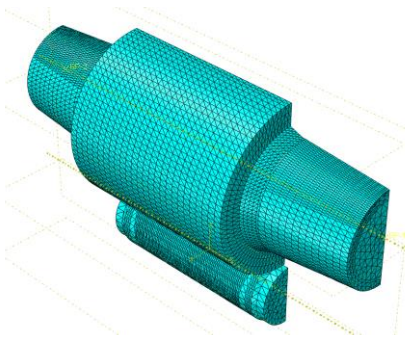


Figure 7. FE mesh.

3 RESULTS AND DISCUSSION

First are presented the deformation results for upwind/downwind simplification.
For Case A it was plotted the final vertical position of line represented by the point 1 (Fig. 8 – left) and for Case B by the point “u” (Fig. 8 – right)

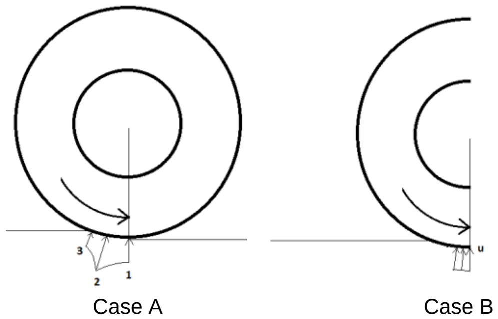


Figure 8. Deformation positions for plotting.

Position 1 and u represent the lowest line of the work roll, which is generally taken as the strip shape, neglecting stress recovery.
Fig. 9 presents the deformation profile for Cases A and B without the application of roll bending forces.

Fig. 10 presents the deformation profile for Cases A and B with the application of roll bending forces.
Inside the strip width it can be seen that both profiles are very similar, with a 4μm maximum difference for the case without roll bending load, and 2 μm for the case applying it.

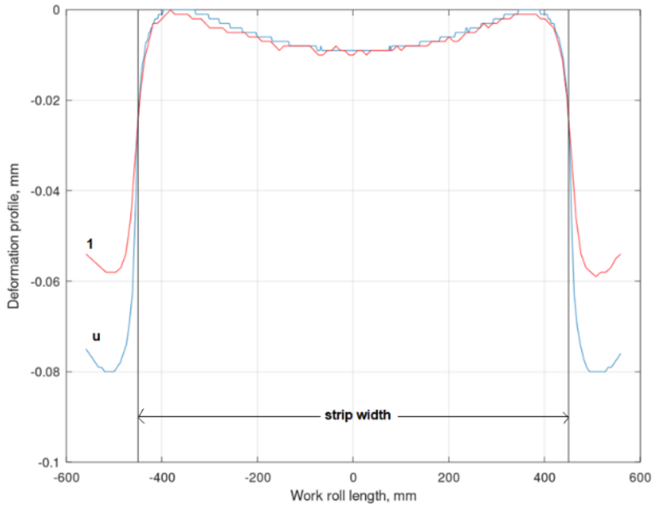


Figure 9. Deformation for Cases A and B, without roll bending.

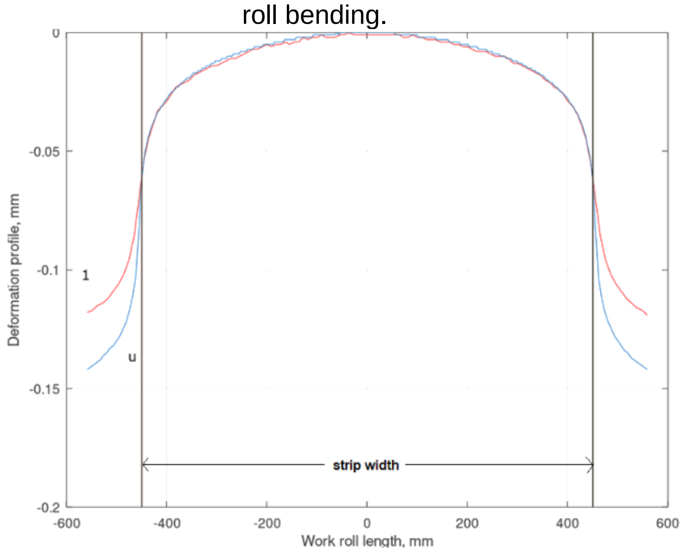


Figure 10. Deformation for Cases A and B, with roll bending.

The second analysis is concerned with the anti-symmetry planes assumption.
Figure 11 clearly shows the stack rotation in this anti-symmetric case: the Intermediate Rolls (IMR) are both sinking more on the left side (darker blue, lighter orange).
Figure 12 shows the contact pressure profile over the top and bottom of the strip. Although not left/right symmetric due to the anti-symmetrically shifting rolls (IMR), they

are identical except for a very localized peak on the right side where a difference shows due to a boundary condition artificially applied on the strip to lock it in the transverse direction.

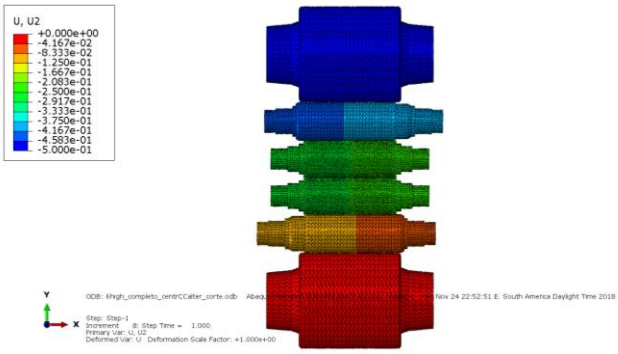


Figure 11. Vertical displacements for the full 6-high rolling mill simulation "as indenting" the strip.

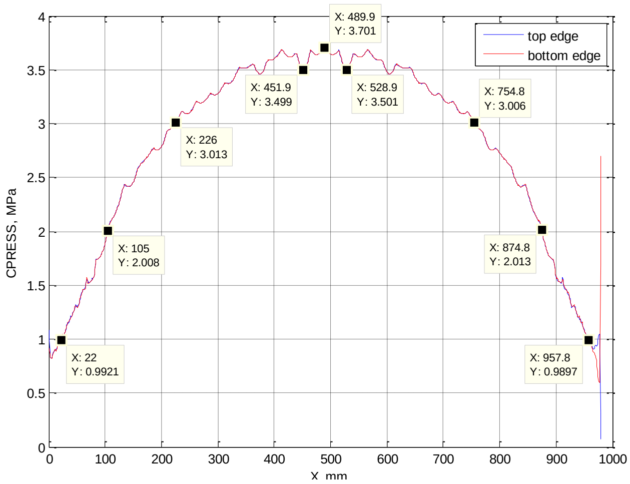


Figure 12. Contact pressures over the top and bottom of the strip.

Figure 13 shows the identical vertical displacements of the top and bottom edges exit lines of the strip, in contact with the work rolls. It can be seen practically identical. The left/right displacement difference corresponds to a rotation around Ox by 0.025 mm / 979.8 mm = 25x10^{-6} rad (0.0015°).

The results for roll neck bearing assumptions are presented next. Fig. 14 presents the vertical displacements of the work roll's lowest line for the six cases analyzed. It can be noted that Cases 1 and 5 are the most rigid ones, and Case 6 the less rigid one.

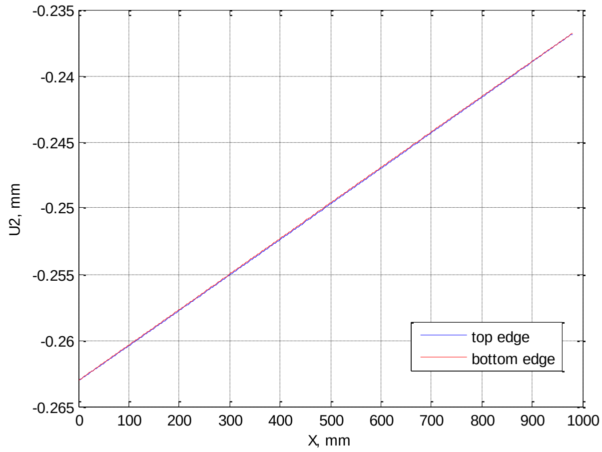


Figure 13. Vertical displacements of the strip.

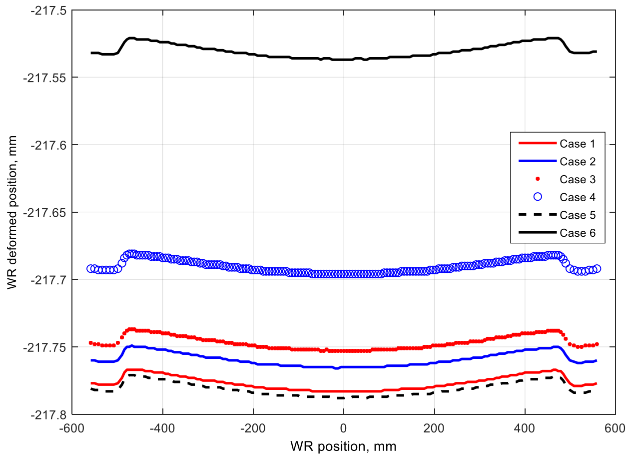


Figure 14. Vertical displacements of the strip for different boundary conditions of backup rolls.

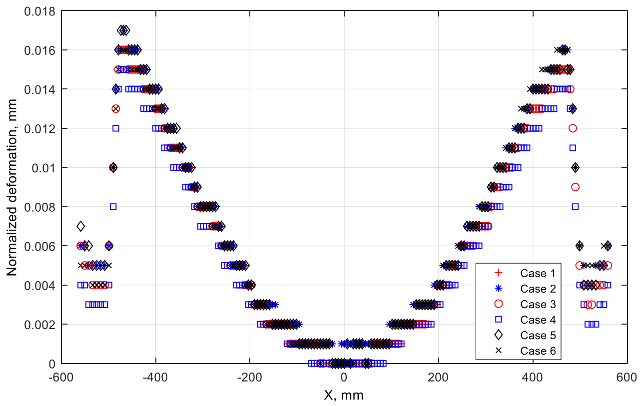


Figure 15. Levelling the curves to zero at the center for all cases.

When they are normalized to zero at the center (Fig. 15), no significant differences on the profiles are noted (2 μm max). It must be commented, though, that the processing speed is 4 times faster when the necks are replaced by couplings (Case 6).

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4 CONCLUSIONS

An analysis of some assumptions made on roll stack deformation calculation by FE models were made. The following conclusions are summarized according to the results obtained:

(1) upstream/downstream symmetry hypothesis: the replacement of the full model with friction-hill load by half-model of the rolling mill under a load uniform in the rolling direction has showed accurate, varying between 2 to 4 μm of maximum differences in deformation.

(2) Vertical and horizontal (anti)-symmetry plane: it was shown that the strip rotation is minimal and the normal contact pressures on the strip keep symmetrical, revealing that these symmetry assumptions are valid for the 3D FEM/Multi-slab method.

(3) Roll neck boundary conditions: 6 Cases were considered, and the results showed that the deformation profiles are very similar, with a maximum of 2 μm difference between them, leading to the conclusion that the best model is the Case 6 (couplings) as they use less finite elements, giving the same results.

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