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## Intra-Ply Shear Locking in Finite Element Simulations

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Intra-ply shear locking is a numerical artifact that occurs during Finite Element forming simulations of fiber reinforced material. It is the inability of standard finite elements to correctly represent the deformation of the material. Intra-ply shearing is the primary deformation mode during forming of doubly curved products. Due to the dominant fiber stiffness, the fabric deforms as a trellis frame. This introduces hinge lines in the fabric. The discontinuity in the shear field at the hinge lines cannot accurately be captured by the finite elements with continuous displacement field.

Hinge lines can clearly be seen in a bias-extension experiment. This experiment is used to characterize in-plane shear behavior of a woven fabric. In a bias-extension experiment three deformation regions develop with different uniform shear angles. When this bias-extension experiment is simulated with an FE simulation, the elements exhibit locking when the element edges are not aligned with the fiber directions. The fibers are strained inside the elements and therefore the elements behave overly stiff and the resulting tensile force is unrealistically high, see *Figure 1*.

Thus, to be able to get the correct response, the mesh has to be aligned with the fiber directions at the beginning of the simulation, but the use is limited. Standard (random) meshers do not take into account the direction of the fibers. Remeshing and local mesh refinement are prohibited during the simulation when the directions of the fibers have to be respected. Moreover, only two fiber directions can be aligned. If multiple composite layers are modeled in an efficient multi-layer element through the thickness, the maximum number of two fiber directions is exceeded. So mesh alignment is not a proper solution for some applications and hence the locking phenomenon has to be solved.

As an aid for solving the locking, two simple patch-tests are developed. The tests have only one hinge line opposed to the complex deformation shape of the bias-extension experiment with multiple hinge lines. The first is a single-element-test where the origin of the locking can be investigated. The second test is a pull-out-test where a small misalignment is introduced in the patch. The new developed elements at least have to pass these tests to be locking-free.

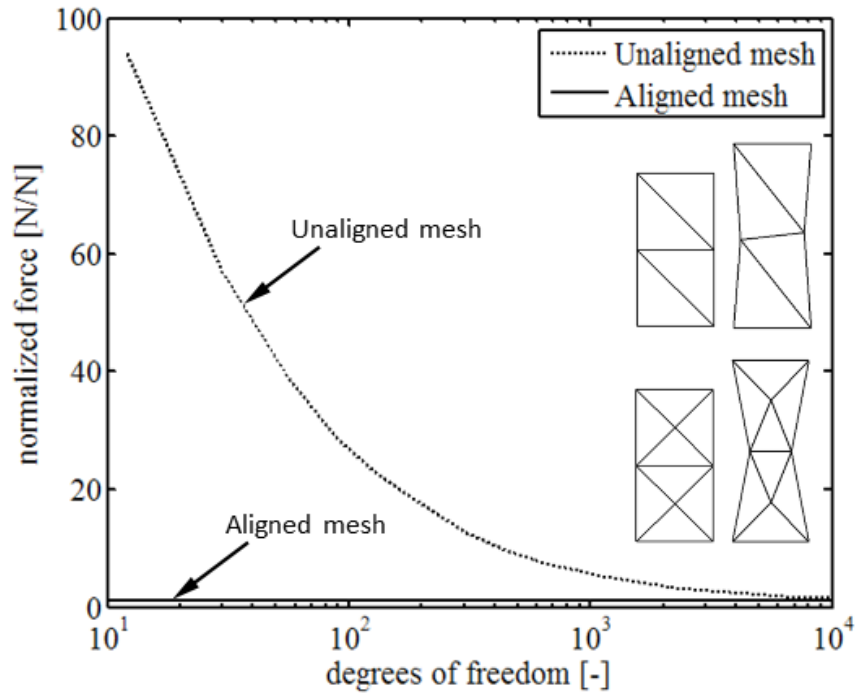


Figure 1: Intra-poly shear locking in a bias-extension experiment when the element edges are not aligned with the fiber directions.