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Wrinkling Analysis of A Kapton Square Membrane under Tensile Loading

Xiaofeng Su and Frank Abdi
Alpha STAR Corporation, Long Beach, CA
and
Barmac Taleghani
U.S. Army Research Laboratory, Vehicle Technology Directorate, Langley Research Center, Hampton, VA
and
Joseph R. Blandino
James Madison University, Harrisonburg, VA

ABSTRACT

A buckling solution and a non-linear post buckling solution were employed for the wrinkling analysis of a tensioned Kapton square membrane. The buckling solution with significantly reduced bending stiffness creates localized buckling modes accounting for the wrinkle formation in the membrane. The non-linear post buckling solution with an updated Lagrangian scheme describes the detailed wrinkle evolution during the loading process. Simulations show wrinkle amplitudes decrease as the tension load increases. The wrinkle number and distribution remain stable until loads exceed a certain level, then new wrinkles occur usually by splitting from existing wrinkles. The evolution of existing wrinkles and formation of new wrinkles in simulations are consistent with experimental observations.

INTRODUCTION

There has been an increasing interest in the application of ultra-light, tensioned thin-film membranes for space structures, including the inflatable sunshield for the Next Generation Space Telescope (NGST), the Inflatable Synthetic Aperture Radar (ISAR), solar arrays, solar sails and solar reflectors. Because of their lack of bending stiffness, membranes cannot sustain compressive stresses. Membranes experience local buckling deformation which is usually defined as wrinkling. The presence of wrinkles in membrane structures may significantly influence static and dynamic behavior of space systems containing membranes. It is, therefore important to develop computationally effective analysis methods for the prediction of wrinkle formation and evolution in membranes.

Wrinkle prediction started with Wagner and Reissner' s work in the 1920s [1] and 1930s [2]. They established a tension field theory, which was further developed by Stein and Hedgepeth [3] in the 1960s to handle more general problems. Miller and Hedgepeth [4] further extended the tension field theory to perform finite element analysis of partially wrinkled membranes in 1982. However, this theory can't give detailed wrinkling patterns with out-of-plane deformation of membrane structures.

To describe realistic wrinkling shapes and their out-of-plane deformation, a buckling solution may be employed. Wong and Pellegrino [5] studied wrinkling formation and evolution of a fully wrinkled membrane panel in shear by buckling and post-buckling solutions using ABAQUS [6]. However, membrane structures in space systems are usually under tension; therefore, in this case they are partially wrinkled. Prediction of localized buckling modes is essential for a valid analysis of partially wrinkled membrane structures.

This paper presents a method to investigate wrinkling formation and evolution in a partially wrinkled structure during the loading process using buckling and post-buckling solutions in GENOA. The updated Lagrangian method [7] is adopted to account for the nonlinear behavior. The wrinkling deformation of a Kapton square membrane under tension was simulated using the aforementioned methods. Analysis results are compared with test data from Blandino et. al. [8]. These methods may provide a useful tool for the design of ultra-light, tensioned gossamer space structures.

MATERIAL, GEOMETRY, BOUNDARY AND LOADING CONDITIONS OF THE SPECIMEN IN THE TEST AND SIMULATION

The specimen is a Kapton square membrane (500mm x 500mm x 25μm (thickness)) with two adjacent corners hung on the tester frame and the other two corners under tension loads [8] (Figure 1). In the simulation, only a quadrant area was modeled for computational efficiency. Symmetrical boundary conditions were applied to the quadrant edges. Since gravity loads are neglected in the simulation, the wrinkling deformation of the quadrant model represents wrinkling deformations at the other three corners.

The material properties of the specimen are as follows:

Kapton – Material of the Membrane
Young's modulus: 2.5 GPa
Poisson Ratio: 0.34
Mylar – Material of the Reinforcement at corners
Young's modulus: 3.6 GPa
Poisson Ratio: 0.3
Kevlar – Material of the Threads by which the tension loads are applied
Young's modulus: 68 GPa
Poisson Ratio: 0.36

METHODOLOGY

Wrinkle formation in tensioned membranes is accounted for by the tensile buckling solution. The wrinkle evolution in the subsequent loading is computed by the non-linear Finite Element Model post-buckling solution with the updated Lagrangian method [7]. The quadrant FEM model has 5,041 nodes and 4,900 elements.

Tensile buckling modes are usually of high order. The tension field theory [3, 9] was adopted to determine the mode of the wrinkling formation.

Determination of Wrinkle Locations and Directions by the Tension Field Theory [9] - Wrinkle locations and directions can be determined by the tension field theory in which the definitions of wrinkle locations and directions are based on signs and directions of principal stresses in the tensioned membranes.

Wrinkle Locations Signs of principal stresses define locations that undergo wrinkling or non-wrinkling deformations in a tensioned membrane:

1). If the major principal stress $\sigma_{11} < 0$, wrinkling does not occur;
2). If the minor principal stress $\sigma_{22} > 0$, wrinkling does not occur;
3). If $\sigma_{11} > 0$, and $\sigma_{22} < 0$, wrinkling occurs.

Wrinkle Directions In wrinkled areas, the major principal stress (σ_{11}) direction is the wrinkle direction at that location. Figure 2 illustrates the major principal stress directions in the quadrant model. The direction of the major principal stress is described with the angle of the major principal stress to the Y-axis in Figure 2. It can be seen that wrinkles emanate from the loaded corner.

Method for the Formation of Initial Wrinkling Patterns by the Tensile Buckling Analysis – Structures normally buckle when in compression. However, membranes buckle even under tensile loads due to their lack of bending resistance. In this case, the tensile buckling deformation of tensioned membranes is called wrinkling. In simulation, the tensile buckling deformation of tensioned membranes can be triggered by significantly reducing the membrane bending stiffness in the buckling solution.

Figure 3 is the quadrant model of the membrane in Figure 1. The buckling modes that have the similar wrinkle locations and directions to those in Figure 2 may be used to account for the wrinkle formation.

Method for the Wrinkle Evolution by the Non-linear Post Buckling Solution with the Updated Lagrangian Scheme [7] - A finite strain post-buckling formulation that is fully nonlinear both in geometry and materials is adopted for the behavior of the membrane. Computational convergence becomes a serious problem for extremely thin membranes. Figure 4 illustrates the basic steps in the non-linear post buckling solution with the updated Lagrangian scheme [7] in the GENOA code. The tension load is applied incrementally. At the end of each incremental loading step, the structural geometry and finite element stiffness are updated for the next step.

In Wong and Pellegrino [5], pseudo inertia and pseudo viscous forces were introduced for computation stability. In this paper, the updated Lagrangian method [7] monitors the in-situ deformation of the membrane structure at each incremental loading step, which helped the computation converge.

RESULTS

The wrinkle evolution of the Kapton square membrane under tension was analyzed using the non-linear post buckling solution with the updated Lagrangian scheme [7] in the GENOA code. The tensile buckling mode in Figure 3 was used as the initial wrinkling shape. The initial maximum buckle amplitude was selected as 12 times the membrane thickness as in [10].

Wrinkle Evolution Patterns of the Kapton Square Membrane - Wrinkle evolution patterns of the quadrant model are shown in Figure 5 at four loads, 0.49N, 1.47N, 2.45N and 4.9N. The 3D plots show the patterns of wrinkle evolution in the membrane during the loading process.

Comparison of Wrinkle Evolution between the Simulation and Experimental Test - Detailed wrinkle evolution patterns were compared to experimental results in reference [8] using 2D contours. The 2D contours of wrinkle patterns of the quadrant model were plotted at loads of 0.49N, 1.47N, 2.45N, and 4.9N in Figures 6 to 9. The contours of simulated wrinkle amplitudes are distinguished by colors.

The simulation shows consistency of wrinkle evolution patterns with experimental test observations. Wrinkle amplitudes decrease as the tension load increases. The wrinkle number and distribution remain stable until the load exceeds 2.45N, then new wrinkles occur in the areas around the center edges of the membrane panel. These new wrinkles usually initiate by splitting from existing wrinkles. The evolution of existing wrinkles and formation of new wrinkles in the simulation agree with test observations in ref. [8].

Comparison of Simulation and Test results for Wrinkle Amplitudes - The wrinkle amplitudes (peaks and valleys) along the 150mm x 150mm corner diagonal (Figure 10) are illustrated in Figure 11. Test results from ref. [8] are also shown in Figure 11 for comparison. Although there are some differences between the simulation and experimental results, particularly near the membrane edges, the simulation shows good agreement with the wrinkle amplitudes from the tests in ref. [8] over a range of load cases.

CONCLUSIONS

1. The tensile buckling solution can account for wrinkle formation in the tensioned membrane.
2. The selection of the tensile buckling mode for the wrinkle formation can be performed based on the tension field theory, which determines wrinkle locations and directions.
3. The updated Lagrangian non-linear solution can simulate the wrinkle evolution in the tensioned membrane. The simulated wrinkle evolution in the tensioned membrane is consistent with test observations:

a) Wrinkle amplitudes decrease as the tension load increases;
b) New wrinkles occur around the center of panel edges after the tension load reaches certain levels.

4. It is necessary to estimate initial buckle amplitudes. An average amplitude of initial wrinkle peaks of 10-15 times of the membrane thickness was an effective choice.

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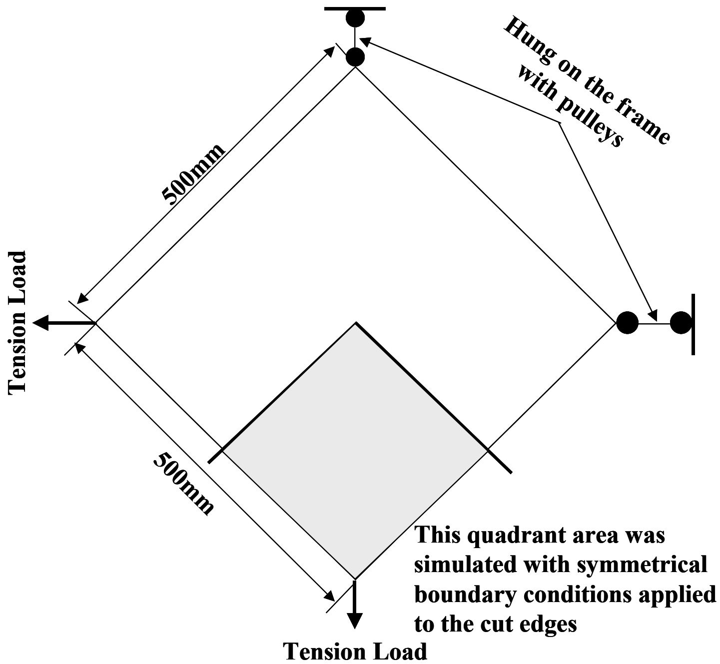


Figure 1 Geometry, boundary and loading conditions of the Kapton square membrane in the experimental test [8] and simulation

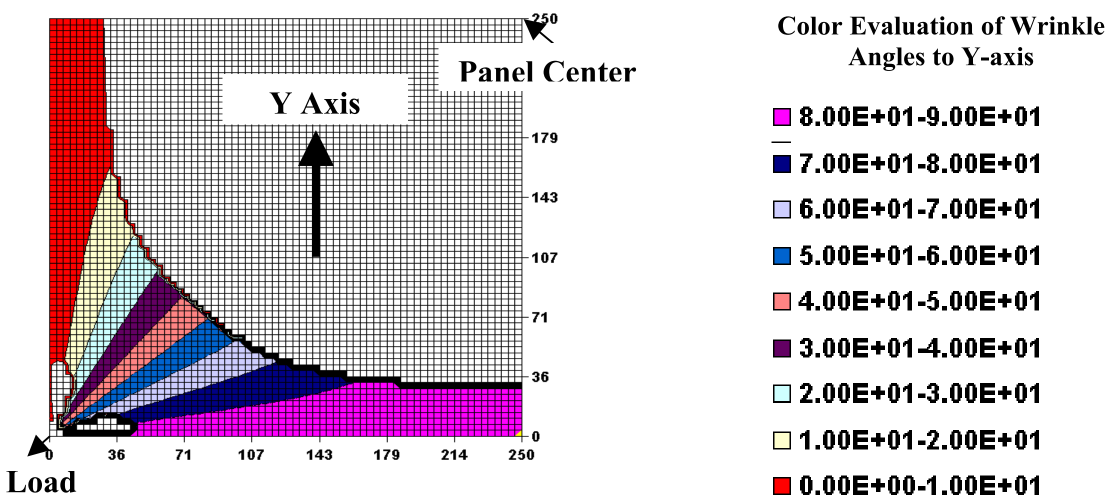


Figure 2 Wrinkle directions (major principal stress directions) in the quadrant of the entire panel in Figure 1 – angles to Y-axis, determined by the tension field theory

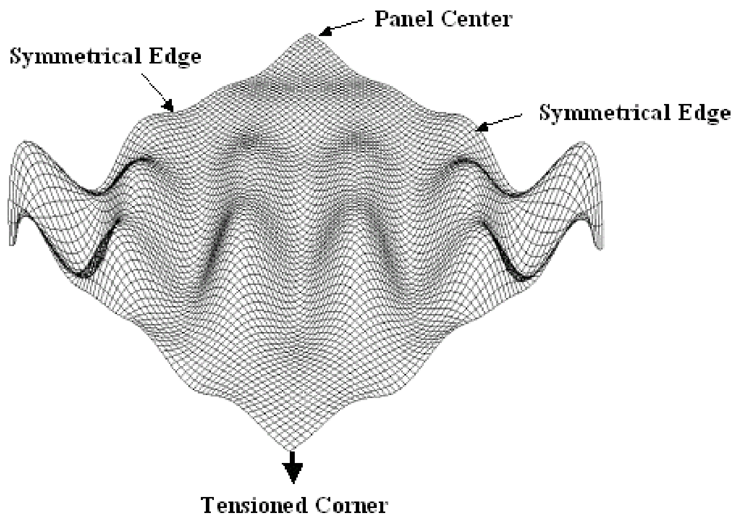


Figure 3 Wrinkle formation in the quadrant model of the Kapton square membrane created by the tensile buckling solution

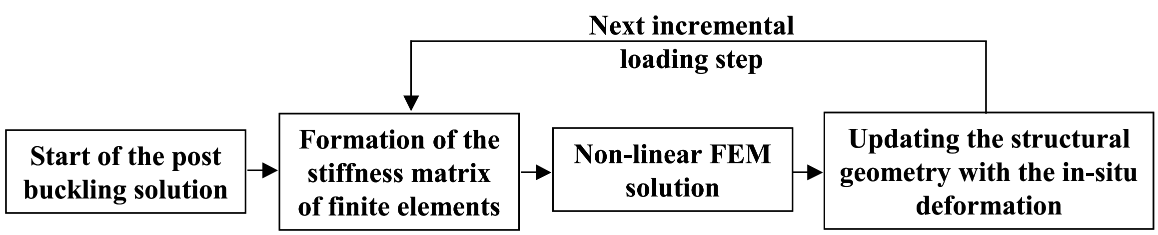


Figure 4 Basic steps in the non-linear post buckling solution with the updated Lagrangian scheme

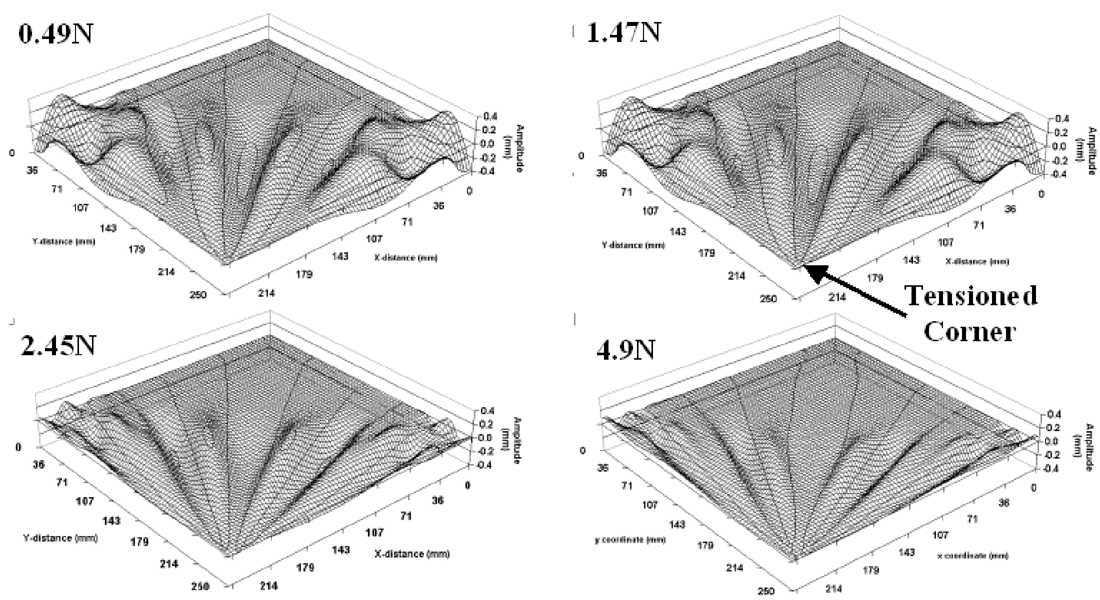


Figure 5 Wrinkle evolution patterns of the quadrant model of the Kapton square membrane at four loads, 0.49N, 1.47N, 2.45N and 4.9N, calculated by the non-linear post buckling solution with the updated Lagrangian scheme

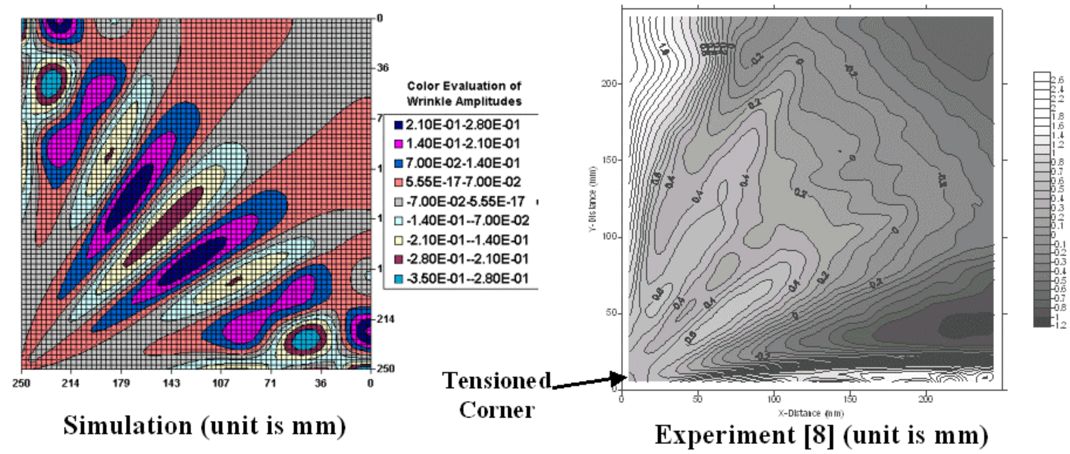


Figure 6 Contours of wrinkle patterns of the quadrant model at load = 0.49N

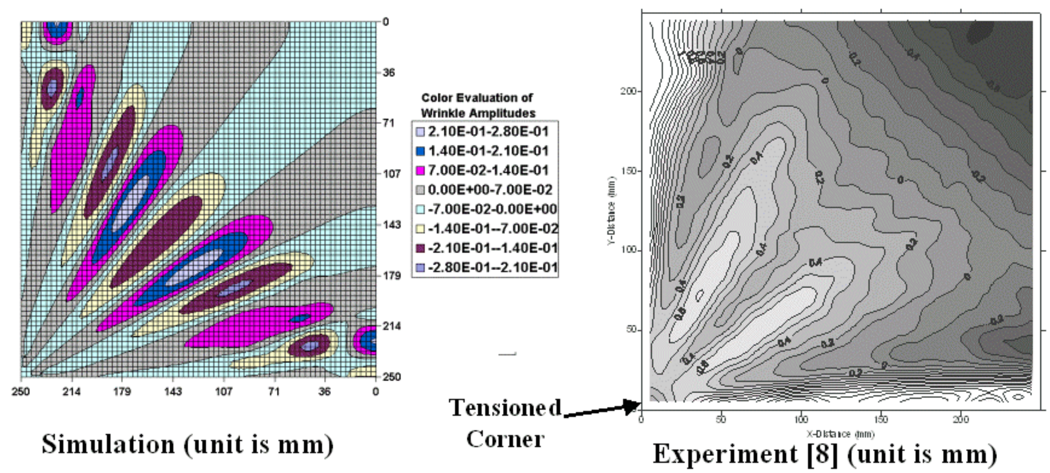


Figure 7 Contours of wrinkle patterns of the quadrant model at load = 1.47N

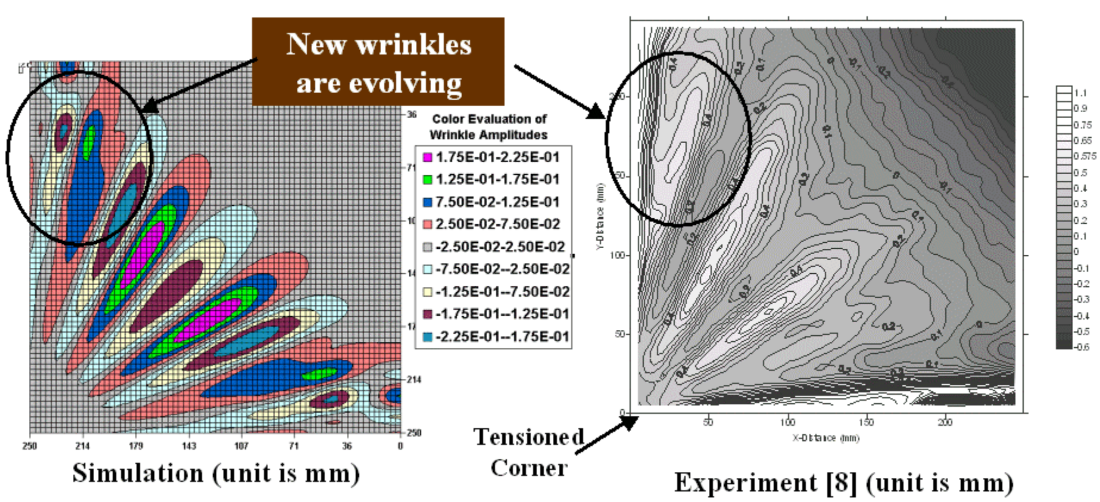


Figure 8 Contours of wrinkle patterns of the quadrant model at load = 2.45N

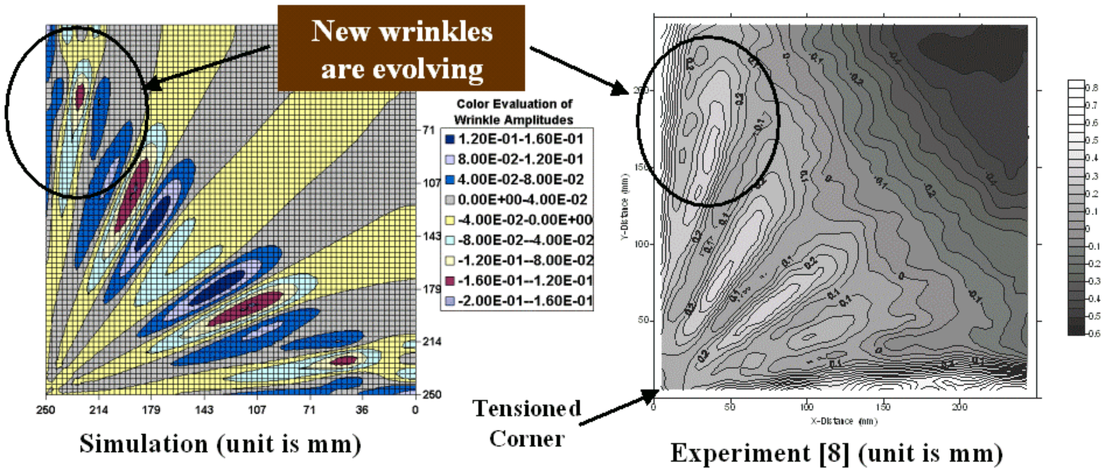


Figure 9 Contours of wrinkle patterns of the quadrant model at load = 4.9N

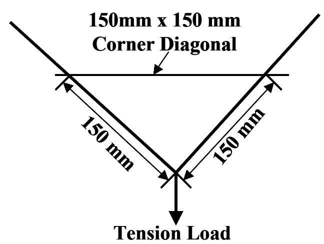
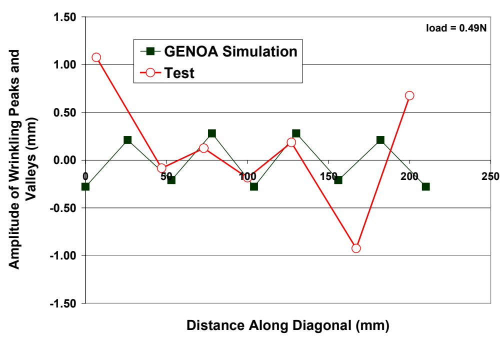
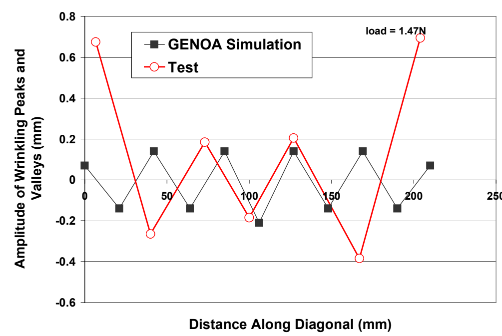


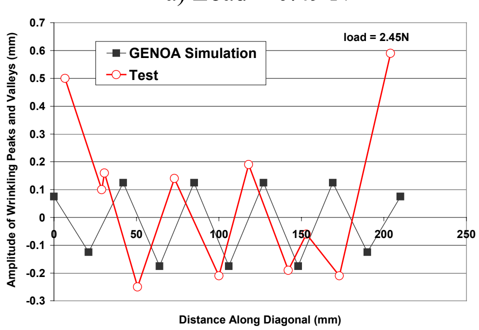
Figure 10 Corner diagonal where wrinkle amplitudes were measured



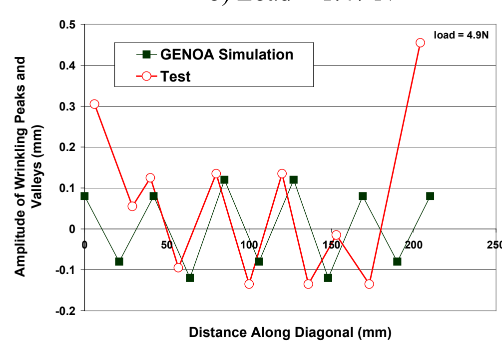
a) Load = 0.49 N



b) Load = 1.47 N



c) Load = 2.45 N



d) Load = 4.9 N

Figure 11 Wrinkle amplitudes (peaks and valleys) along the 150mm x 150mm corner diagonal at various loads. Comparison of the simulation and test (reference [8]) results