Characterization of a Flexible Device using a 3-Point Rolling Test

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***Abstract*—Mechanical reliability is the one of the critical aspect of flexible or foldable electronic devices. As new flexible components emerge, new paradigms for mechanical testing and simulations will be required. Standardized characterization test methods such as the 3-point bend test only account for small displacements and large radius of curvature and might not be applicable to foldable device as is. In this paper we propose a 3-point rolling test setup that can be used to achieve a range of radius of curvature. Additioanlly we evaluate the strain response of the device using an equivalent simulation model. We further evaluate the effect of different design parameters like layer thickness and modulus on the reliability of the device using a Taguchi design of experiments.**

I. Introduction

Flexible and foldable device design has been an active area of research recently. Most ongoing research and development has been focused on flexible displays, sensors, batteries and other subsystems. Many leading technology firms have been exploring the opportunities in flexible mobile devices to integrate bendable displays and other flexible subsystems, such as Lenovo CPlus [1] and Nokia Morph [2]. While a foldable or a flexible mobile device can bring new innovations in form-factor design and user interaction, such as the HoloFlex [3], it also has unique design challenges. From a structural design perspective, a flexible phone has unique failure modes that are typically not seen in a conventional phone.

A foldable phone would typically constitute a flexible cover glass and display assembly that runs through the length of the device and folds about a hinge. Figure 1 shows the typical stack-up of a cover glass-display assembly. This would be one of the most critical components in the system as it would undergo repeated bending as the device is folded. Figure 1 also shows the potential failure modes (creep, fatigue, buckling, and delamination) that can be expected at different fold states of the device. The severity of the fold and the corresponding stress distribution is a function of the display assembly stackup and the bend radius of the device.

In this paper, we propose an experimental setup to evaluate different foldable phone designs and study their mechanical reliability. 3-point or 4-point bend experiments are typically used for characterization but the displacement is usually small and radius of curvature is large. As foldable devices experience significantly large flexion with a relatively smaller radius of curvature, we propose a 3-point rolling fixture that supports biaxial loading. We use an equivalent simulation model to study the bending behavior of a simplified foldable device. Additionally, we also determine the effect of design parameters, like the thicknesses of individual components in the display assembly, on the device reliability using the Taguchi design of experiments (DoE) approach. Our study is currently limited to a quasi-static flexural loading as the study of fatigue, creep, and delamination behavior requires sophisticated material models that can also not be generalized.

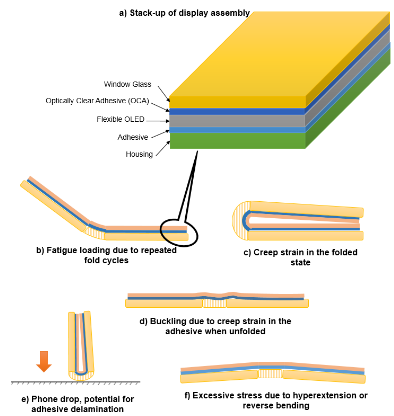

Fig. 1. (a) Stack-up of a typical display and cover glass assembly in a phone, (b)-(f) Potential failure modes in a foldable phone.

II. Literature Review

In literature, bending behavior of flexible systems has been studied through analytical, simulation and experimental methods. The mechanical reliability of flexible devices has been broadly studied by Harris et al. [4] and Rogers et al. [5] where they have identified a generic set of mechanical failure modes and stated design approaches to mitigate them.

Shi et al. [6] have shown that for a stack of composite beams, using very low elastic modulus material in the middle can separate the neutral axes for the attached top and bottom layers. This separation is achieved because the shear coupling between the top and bottom layer is reduced as the middle layer can function with large shear strains. A simplified analytical model is formulated to calculate neutral axes positions

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and strains on the three layers. Li et al. [7] and Lee et al. [8] have also presented an analytical method for bending of composite beams and to determine the corresponding strain distribution. They suggest that brittle materials like glass should be placed close to the neutral axis to lower the bending strain. According to Li et al. the length to thickness ratio plays an important role in the splitting of neutral axes. The above papers analyze a device construction that is very similar to a foldable phone display assembly where plastic and glass layers are bonded using adhesives with significantly low elastic modulus. Niu et al. [9] have proposed a methodology to reduce the critical bending radius of a flexible AMOLED display. They demonstrate that the critical bending radius of the display can be reduced from 7mm to 4mm by modulating layer thickness of the individual layers in the stack.

The effect of adhesive stiffness has been studied by Salmon et al. [10] using a finite element model. They have compared the performance of two 3M optically clear adhesives (OCA) which are modeled as linear viscoelastic materials in the simulation. A simulation model of creep and buckling deformation indicates that the performance of the display is governed by the system level response and OCA plays a critical role in the same. Cheng et al. [11] have used Taguchi design of experiments to lower the bending stress in OCA in a touch panel display by 16% using an additional protective structure.

In our work, we use a 3-point rolling setup to study the deformation of the foldable display assembly. Additionally, we study the impact of thicknesses of individual components on the strain response and device reliability. We use the Taguchi design of experiments method to minimize the number of simulation runs and assess the trend.

III. Design of 3-point Rolling Experiment

The structural reliability of a component or a subsystem is primarily driven by its geometry and material properties. For example, to determine the reliability of the display module in a foldable phone, we would first individually characterize its different constituent layers and identify its failure modes. The material properties would typically be determined through quasi-static and dynamic tensile, shear and compression tests using standardized specimen geometry. Typically a validation experiment would be performed to correlate the experimental and simulation response in a mixed mode loading like 3-point bending.

One of the challenges of using a standard 3-point bend fixture for a foldable device is the need for a narrow bottom span of the rollers to achieve a smaller radius of curvature. We propose a fixture design where the bottom rollers are translated laterally towards each other and in sync with the downward travel of the top roller (Figure 2). The lateral movement ensures that we achieve the required radius of curvature eventually and the applied force gradually builds up as the device is folded. The lateral movement is controlled by a gear assembly which is driven by an electric motor. The gear assembly converts the rotation of the motor to synchronized lateral movement of the two bottom rollers in the opposite direction.

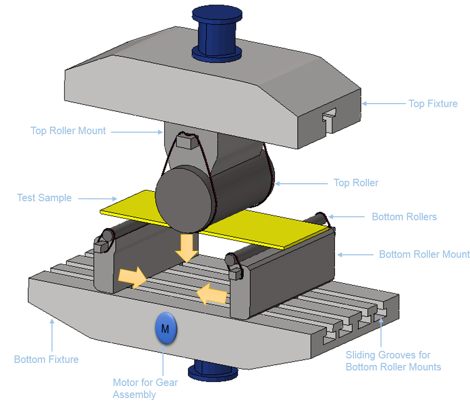


Fig. 2. CAD model of the proposed 3-Point rolling experimental setup for a foldable device.

For any given radius of curvature (R_c) and thickness of the test sample (t), the speed of the top roller (V_T) and the bottom rollers (V_B) is related as,

$$V_B = V_T \left(\frac{k}{R_c + t} - 1 \right) \tag{1}$$

where $2k$ is the span of the bottom rollers placed symmetrically apart from the top roller. Typically there are guidelines for roller displacement speeds for quasi-static loading, which would then determine the widest bottom span allowed. The rollers are fitted on mounts which makes it possible to alter the top roller to correspond to the radius of curvature of the device.

An important aspect of any mechanical characterization experiment is to reduce the complexity of the boundary conditions so that it can be correlated with an equivalent analytical formulation or simulation. This ensures that the equivalent simulation model can be validated through the experiment and thus design iterations can be performed using simulation models. Similar bending test machines are available in the literature, where the ends of the test sample are clamped in a jaw. This can lead to intangible contact stresses that cannot be accurately reproduced in a simulation model. Liu et al. [12] have proposed a bending test apparatus that constrains the ends of the test sample using a rectangular channel. The channels are brought together to bend the test sample but there is no control on the radius of curvature. Niu et al. [9] also mention a test setup in which radius of curvature is not controlled and is calculated after the experimental procedure. Bell et al. [13] propose having a roller to control the radius of curvature but the ends of the test sample are clamped which can introduce localized stresses. The 3-point rolling setup proposed in this paper imitates a standard 3-point bend test and is similar in principle to a simply supported beam. The response from the 3-point rolling test can also be validated with the analytical models proposed in the literature by Shi et al. [6] and Li et al. [7].

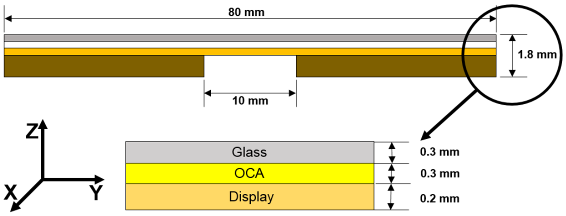


Fig. 3. Stack-up of the glass-display assembly model used in the simulation.

IV. Simulation Model of 3-Point Rolling Test

We use a finite element model of the foldable phone to evaluate the deformation and the corresponding strains when the device is flexed. This simplified model has a cover glass and a flexible display bonded to it through a soft OCA. The bottom surface of the display is bonded to a rigid chassis that provides structure to the device. Typically, other components would be part of the stack-up but for simplicity we have considered only the critical layers as shown in Figure 3. The dimensions of the device are 80 mm × 50 mm × 1.8 mm.

The nonlinear quasi-static simulation is run in LS-DYNA^{TM} implicit solver. Mechanical properties of the layers used in the simulation are detailed in the Table I. We assume linear elastic material properties for the all the components except the OCA which has a hyperelastic material model. We use the *MAT_OGDEN material model to model the behaviour of OCA. This model is based on uniaxial tensile and compression test data generated from experimental data of a representative OCA sample (Figure. 5). An 8-node brick element is used for modeling all the components. The element sizes are within 0.05-1.0 mm with a maximum aspect ratio of 15. We represent the 3-point rolling fixture using three rollers with a diameter of 3.5mm. The bi-axial displacement is specified to the rollers simultaneously to simulate the 3-point rolling experiment.

Figure 4 shows the strain contour on the three critical components of the glass-display assembly for the baseline dimensions mentioned in Table I. It is seen that the bending strain on the cover glass and display is significantly higher than typical failure strengths of these materials. We, therefore, run a design of experiments to determine the design parameter that can lower the strain on these components.

TABLE I
Dimensions and Properties of the Baseline Simulation Model

Layer Name	**Material**	**Thickness** (mm)	**Young's Modulus** (MPa)	**Poisson's Ratio** (ν)
Top Cover	Glass	0.3	70000	0.3
OCA	Liquid OCA	0.3	≈ 0.68 (Hyperelastic)	0.4955
Display	Plastic	0.2	2500	0.3
Housing	Rigid	1.0	2.1E+05	0.3

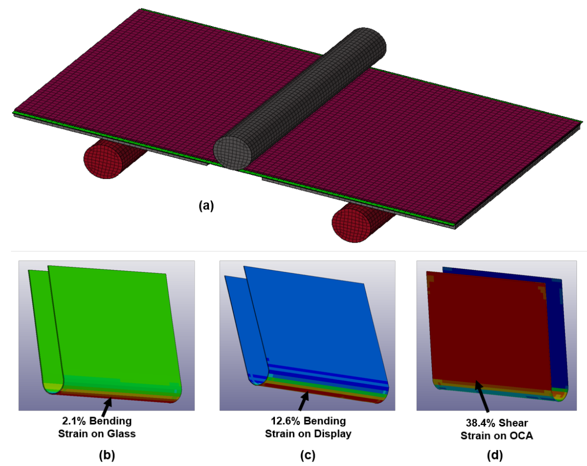


Fig. 4. (a) Simulation model for the 3-point rolling test, (b), (c), (d) Strain contour plots of the cover glass, display, and OCA.

V. Taguchi Design of Experiments Study

The design parameters that can most likely be modified in the assembly are the thickness of the cover glass, display, and OCA layer. Additionally, the stiffness of the OCA can be varied within a given range. The material properties of the cover glass and display are not considered as variables in this study as their range of variation is not expected to have a significant impact on the bending response of the system. The four parameters chosen for this study are listed below:

1) Glass thickness (GLS_THK)
2) OCA thickness (OCA_THK)
3) Display thickness (DSP_THK)
4) OCA material (OCA_MAT)

If we were to study the impact of each of the 4 design variables and perform a DOE with 3 levels, we would require a total of 81 runs. We instead use the Taguchi DOE procedure to reduce the number of runs and identify the critical design parameters that impact glass and display strain response. The three levels for each design parameter is tabulated in Table II.

The three different hyperelastic material models used for OCA are tabulated in Table III. We use the Ogden material model with N=3 for the simulation. The baseline model is derived from test data of an elastomer with comparable properties to OCA. The other two models are derived from the same by scaling the data by a factor of 0.1 and 10. This range of modulus should capture the typical range of OCA

TABLE II
Levels of the Parameters for Taguchi Design of Experiments

Levels	**GLS_THK (mm)**	**OCA_THK (mm)**	**DSP_THK (mm)**	**OCA_MAT (MID)**
1	0.10	0.10	0.10	1
2	0.20	0.20	0.15	2
3	0.30	0.30	0.20	3

TABLE III
MATERIAL CONSTANTS FOR OGDEN MATERIAL MODELS IN LS-DYNA™

Material ID	μ_1	μ_2	μ_3	α_1	α_2	α_3
1(0.1x Baseline)	2.145	-0.01	-2.1E-10	7.3E-4	-4.9	-46.8
2(Baseline)	21.45	-0.13	-2.1E-09	7.3E-4	-4.9	-46.8
3(10x Baseline)	214.5	-1.36	-2.1E-08	7.3E-4	-4.9	-46.8

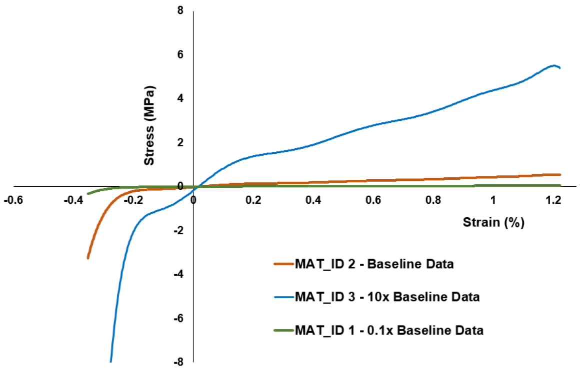


Fig. 5. Engineering Stress-Strain Data for the Three Hyperelastic material models used in the Taguchi Analysis

stiffness. The corresponding engineering stress-strain plots is shown in Figure 5.

A. Results of Taguchi Design of Experiments

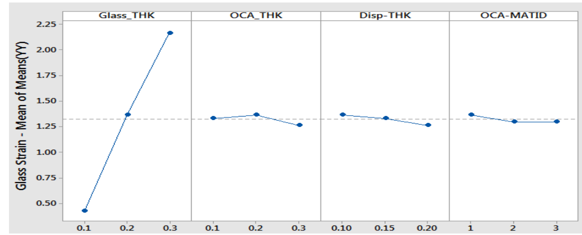
The objective of the DOE is to determine the design parameter that lower the bending strain on the cover glass and display and the shear strain in the OCA. These can be referred to as below, where the subscript of strain follows the coordinate system in Figure 3.

1) Maximum tensile strain ($\mathcal{E}_{yy}$) on cover glass
2) Maximum tensile strain ($\mathcal{E}_{yy}$) on display
3) Maximum shear strain ($\mathcal{E}_{yz}$) on OCA

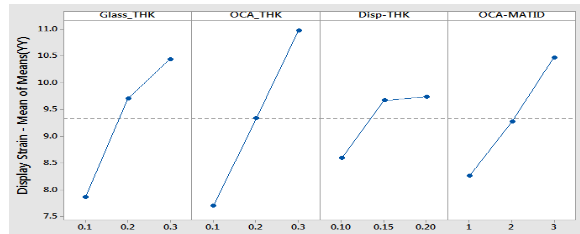
The sensitivity plots of the strain with respect to the design variable is shown in Figure 6. As our objective is to minimize the strain response, lower values of strain in the mean effects plot are preferred.

TABLE IV
TAGUCHI L9 ORTHOGONAL ARRAY FOR DESIGN OF EXPERIMENTS

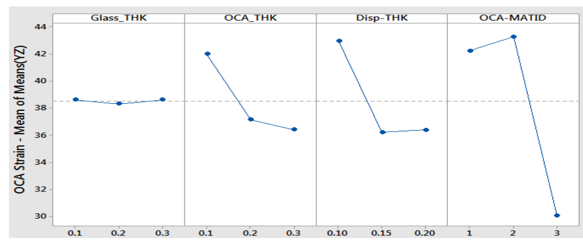
Iteration Number	**GLS_THK (mm)**	**OCA_THK (mm)**	**DSP_THK (mm)**	**OCA_MAT (MAT ID)**
1	0.10	0.10	0.10	1
2	0.10	0.20	0.15	2
3	0.10	0.30	0.20	3
4	0.20	0.10	0.15	3
5	0.20	0.20	0.20	1
6	0.20	0.30	0.10	2
7	0.30	0.10	0.20	2
8	0.30	0.20	0.10	3
9	0.30	0.30	0.15	1



(a) Mean effects plot for cover glass strain



(b) Mean effects plot for display strain



(c) Mean effects plot for OCA strain

Fig. 6. Effect of design variables on the strain response - (a) maximum bending strain on the cover glass, (b) maximum bending strain on the display, (c) maximum shear strain in the OCA.

Here are the key takeaways from the DOE:

- The cover glass strain is directly proportional to its thickness, as is expected. Other parameters have a negligible effect on it bending strain. So a low thickness cover glass should be preferred.
- Bending strain in the display reduced with thinner cover glass, display and OCA with a strain reduction of up to 30%. A softer OCA also lowers the strain on the display.
- OCA strain reduces with a thicker display and OCA layer by up to 10% within the considered thickness range. Also, Higher stiffness of the OCA should be preferred to lower the shear strain.
- To achieve a reduction in all the strain responses, the thickness of OCA is a conflicting parameter as lower thickness reduces display strain by increases OCA strain and vice versa. Similarly, the material modulus of the OCA has a greater effect in reducing the OCA strain versus the increase in display strain.

Based on the results of the study we propose the two following combinations of optimal parameters (1) GLS_THK 0.1mm, OCA_THK 0.1mm, DSP_THK 0.2mm, OCA_MAT MID 3 (2) GLS_THK 0.1mm, OCA_THK 0.3mm, DSP_THK 0.2mm, OCA_MAT MID 3. We run the corresponding simulations to verify the strain response and compare the reduction

TABLE V
COMPARISON OF THE RESULTS FOR BASELINE AND OPTIMAL DESIGN COMBINATION

Parameter	Baseline Model Strain	Optimized Model Strain	Improvement in %
Maximum tensile strain ($\mathcal{E}_{yy}$) on cover glass	2.10	0.40	80.0%
Maximum tensile strain ($\mathcal{E}_{yy}$) on display	12.60	7.60	39.6%
Maximum shear strain ($\mathcal{E}_{yz}$) on OCA	38.40	26.10	32.0%

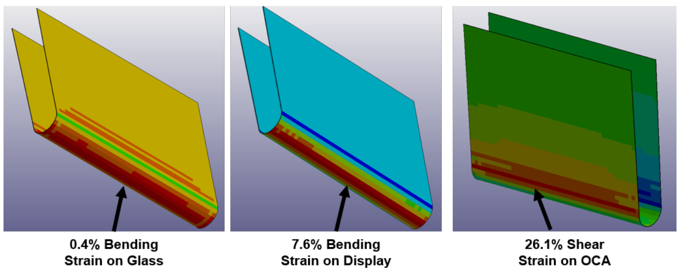


Fig. 7. Simulation result from the optimized run

from the baseline model. It is seen that design option (1) with thinner OCA layer is better than option (2). Table V shows that the proposed optimal combination of design parameters has a significant reduction (up to 30-80%) in strain over the baseline model. Figure 7 shows the strain contour plot for the optimal design combination.

VI. CONCLUSIONS

The paper presents an approach to characterize foldable devices under flexural loading and proposes a 3-point rolling test setup to achieve a low radius of curvature. An equivalent simulation model is developed to understand the strain response of the device as it is folded. A Taguchi DOE is performed to determine the impact of thickness and modulus of the layers in the cover glass-display assembly. The strain response is studied through simulation and its seen that lower thickness of the cover glass, display and OCA significantly reduces the tensile and shear strain in the components. Also, a stiffer OCA considerably reduces the shear strain in the OCA. The study presented in this paper captures dimensional variations within a limited range but does capture the trend would be applicable when identifying the optimal design within a set of design choices. Besides flexural loading, mechanical reliability of a foldable device would also involve studying its creep, fatigue, buckling, and dynamic behaviour which would be considered in future evaluations.

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