Modeling the Mechanical Performance of Bendable Display under Cyclic Loading

Mukunda Madhava Nath[1*], Gaurav Gupta[1]*
[1]*Advanced Technology Lab, Samsung R&D Institute India - Bangalore, Bengaluru, India*
*Contact: m2.nath@samsung.com, g1.gupta@samsung.com

Abstract— **Bendable displays used in foldable phones have a stack-up of multiple substrate layers bonded by a soft adhesive. The material property of the adhesive layer has a significant impact on the bending and shear deformation behaviour. In this paper we evaluate the impact of adhesive material on the cyclic fold-unfold behaviour of a simplified display assembly using finite element simulations. We use a viscoelastic material model for the adhesive to represent its time dependent behaviour and assess the residual stress over repeated load cycles. A comparison of the system's response to two material models is done to evaluate the factor that drives the residual stresses in the display.**

I. Introduction

The mobile industry in the past year has seen a keen interest in foldable phones and many commercial devices are expected to be available later this year [1] [2]. The flexible electronic component in these phones is currently limited to the display, which in itself is an extremely challenging technology. Evaluating the mechanical reliability of the bendable display under small bend radii and cyclic loads is essential for a robust foldable phone design.

The reliability of a device is conventionally evaluated using experimental and numerical simulation methods. In this paper we propose to use finite element simulation to evaluate the deformation of the bendable display. The bendable display typically consists of multiple polycarbonate substrate layers bonded together by soft optically clear adhesives (OCA) [3] [4]. These layers are extremely thin, of the order of 10-100 microns and thus pose a significant challenge to the accurate prediction of their deformation behaviour.

A foldable phone typically has two key configuration when in use, an open state when the system is in a stress-free state and a folded state when the display assembly is at the highest stress state. The device is expected to be in either of these states for a considerable amount of time. It is therefore necessary to understand the impact of cycling through these two extreme stress states repeatedly over the life of the device. In this paper we limit our study to a subassembly of the display module, consisting of 2 polycarbonate layers bonded by a soft OCA material. The proposed approach can be extended to evaluate the complete display stack-up. We use a linear viscoelastic material model for the OCA to represent it's time-dependent behaviour. It is expected that the system's response would be affected by the creep and stress relaxation behaviour of the OCA material.

II. Literature Review

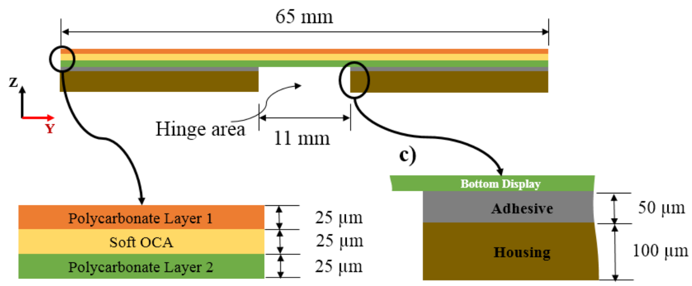

Fig. 1 Simplified multilayer stack-up of a foldable phone used for simulation along with the dimensions of each layer.

There have been some recent publications on the analysis of bendable displays using analytical and numerical methods supported by experimental validations. The work by Shi et al. [5] proposes a strain energy based analytical formulation to determine the stress state in a three layer stack-up. Li et al. [6] have proposed another analytical formulation that uses a similar approach but also computes the shear strain of the soft adhesive layer. They have shown that the strain profile through the thickness of any layer is a function of length of the layer as well. One of the limitations of these analytical formulations is the boundary condition, as it requires that each layer has free ends. In a typical display assembly, each layer is very likely to be constrained at the ends and therefore the above analytical formulation might not be applicable. Nevertheless, the formulation provides a general trend of the system's behaviour with changes in the design parameters.

Numerical methods have also been used to predict the strain profiles in a flexible multilayer stack-up. Salmon et al. [3] have used finite element analysis to compare the performance of the display assembly for two different OCA materials. They have used viscoelastic material models for the OCA to study the time-dependent behaviour. Their work evaluates the effect of stress relaxation in the OCA after a single fold-unfold cycle but the impact of repeated folding is not evaluated. Jia et al. [4] have demonstrated the effect of different stack-up constructions, with the layer thickness and material being the design variables and the OCA modelled as a viscoelastic material. Niu et al. [7] have used an experimental approach to determine the onset of failure of a display assembly as the bend radius is reduced. They have further used an analytical model to optimize the thicknesses of the display stack-up and subsequently demonstrated through experiment that the proposed design is

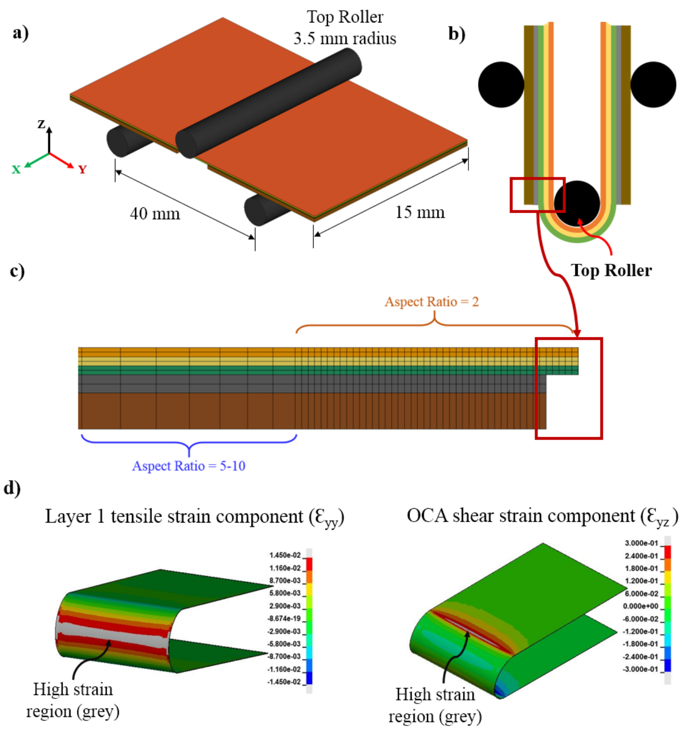

Fig. 2 (a) 3-point bend setup used in simulation, (b) Final folded state of the simplified assembly, (c) Varying mesh refinement used through the length of the layers to optimize for computational time, (d) Strain contour plot for Layer1 and OCA for a linear elastic material model.

indeed superior. Nath et al. [8] have also demonstrated the display's performance as a function of design parameters - OCA material modulus and thickness of each layer. They conclude that the material stiffness is the most critical parameter in determining the system's reliability.

The work presented in this paper is primarily to study the performance of a display assembly under cyclic loading for a given viscoelastic OCA material. There have been numerical methods that have been proposed in the past but none have evaluated the residual strain in the OCA after each unload cycle and its cumulative effect on the device's reliability over repeated load-unload cycles.

III. Simulation Modeling Approach

To represent the folding state in a foldable phone, we use a 3-point bend setup as shown in Fig. 2(a). The top and bottom roller displacements are controlled so that we achieve a 180° fold as shown in Fig. 2(b). The bend radius of fold is controlled by the radius of the top roller. In our analysis we have used a roller of radius 3.5mm, but in a foldable phone the radius is expected to be much smaller.

In a typical construction of a foldable phone, the display assembly will be bonded or constrained to the phone housing so that the display's bendable region is confined to the centre where the hinge is placed. For the analysis presented in this paper, we have used a simplified display stack-up of 3 layers that is bonded to a rigid plate which represents the housing of a typical phone. Fig. 1 shows the model used for the simulation analysis. The size of a typical foldable display is around 150mm x 150mm but we have taken a reduced size of 65mm x 15mm as it significantly reduces the computational time without compromising on accuracy of the results. It is observed in the simulations that the edge effects in the strain profile are not affected by the reduced width.

In our model, each of the display layers has a 25 micron thickness but the length and width dimensions are significantly higher. So when discretising the model for the finite element simulation, it is important to ensure that the element aspect ratio is not too high as it can affect the strain prediction. Given the limited compute power, we use a fine element grid with aspect ratio of 2 only at the centre of the display where the highest strains are expected. The mesh gradually gets coarse towards the ends with the aspect ratio being 10 or higher as shown in Fig. 2(c).

In the absence of an appropriate analytical model to validate the simulation model, we have compared the strain predictions from two commercial finite element solvers – LS-Dyna and Optistruct. A linear elastic material for the OCA is used for this comparative study. The rollers are modelled as rigid and material properties of the other layers is indicated in Table I. Table II summarizes the results from the two solvers and the difference in strain prediction is less than 3% of each other. This confirms that the modelling approach we have used is correct and consistent. Fig. 2(d) shows strain contour plots for the display and OCA components. The location of high stain in the OCA, when completely folded, is near the transition of the unsupported central region and the region bonded to the housing. The location of the high OCA shear at the transition region is consistent with prior literature [3] [4].

The following section discusses the results from cyclic loading of the simplified display assembly. A linear viscoelastic material model is used for the OCA. All subsequent simulations are run in LS-Dyna given the solver's capability to model viscoelastic materials.

TABLE I
Material Properties of the Layers

Layer Name	Elastic Modulus (MPa)	Poisson's Ratio
Polycarbonate Layer 1	2,000	0.30
Soft OCA	0.01	0.45
Polycarbonate Layer 2	2,000	0.30
Adhesive	100	0.30
Chassis	210,000	0.30

TABLE II
Comparison of Strain Predictions for OCA modulus of 0.1 MPa

Max Bending Strain	LS-DYNA Implicit	Optistruct	Error (%)
Layer 1	-1.20	-1.20	0
Layer 2	+1.51	+1.47	3

TABLE III
HYPERELASTIC MODEL CONSTANTS FOR REFERENCE MATERIAL

Hyperelastic Constant	Value in MPa
C10	6.74E-3
C20	-2.51E-4
C30	-7.53E-6

TABLE IV

PRONY CONSTANTS FOR REFERENCE VISCOELASTIC MATERIAL OF OCA

i	Relative Modulus (g_i)	Time Constant (τ_i)
1	0.59019	0.01875
2	0.14605	0.20843
3	0.11153	1.86750
4	0.06431	19.1670
5	0.03522	233.070

IV. SIMULATION OF CYCLIC LOADING

A viscoelastic material model is required to simulate the time-dependent deformation behaviour of the OCA. We have used the OCA material model by Jia et al. [4], which has a hyperelastic behaviour as detailed in Table III coupled with a viscoelastic material model defined by a Prony series (Table IV). The Prony series is a representation of the relaxation behaviour of a material as a function of time. This is typically generated from the frequency dependent storage and loss modulus of the material (Fig. 3). While the storage modulus dictates the elastic behaviour of the material, the loss modulus represents the damping or viscous behaviour.

A. Simulation Model

The response of the display assembly is first evaluated for a single fold. As shown in Fig. 4, the assembly is folded in the first 2 seconds and the highest stress is observed in the OCA layer. When the folded state is maintained, the stress gradually relaxes because of the viscoelastic material behaviour of the OCA. It takes about 120 seconds for the stress to stabilize.

We further evaluate the response when the display is unfolded after 20 seconds in the folded state. It is seen that the shear stress in the OCA changes direction (negative) and then gradually settles. It takes about 65 seconds to reach a stress free state. These experiments indicate that there could be cumulative effect of viscoelastic behaviour when the display is repeatedly folded and unfolded in short time spans.

Fig. 5 shows a scenario where the display is cycled through multiple fold-unfold states in which a single cycle is of 44 seconds. The display assembly is first folded in 2 seconds and then held in the folded state for 20 seconds. The device is then unfolded which takes 2 seconds and is held in the unfolded state for 20 seconds. This constitutes a single fold-unfold cycle and is repeated 4 times to determine the cumulative effect of residual stresses in the display. Ideally the residual stresses after each cycle should be zero or nearly zero. But as the OCA is viscoelastic, there is considerable residual stress which adds up after each cycle.

B. Discussion of Results

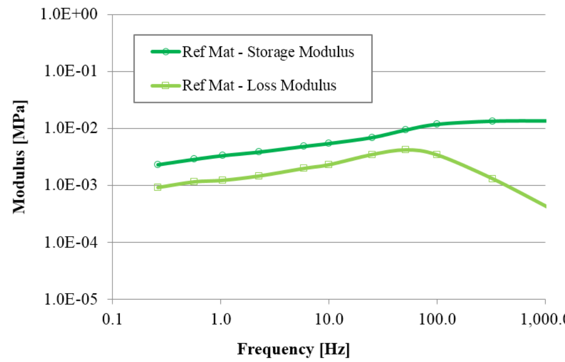

Fig. 3 Storage and loss modulus as a function of loading frequency for the OCA reference material from Jia et al.

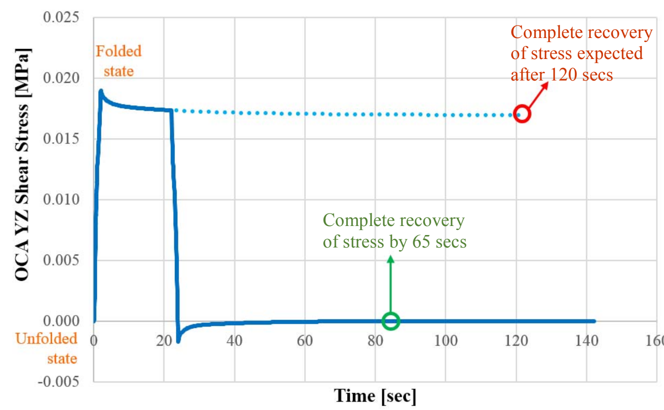

Fig. 4 OCA shear stress relaxation when the display is held in the folded and unfolded state.

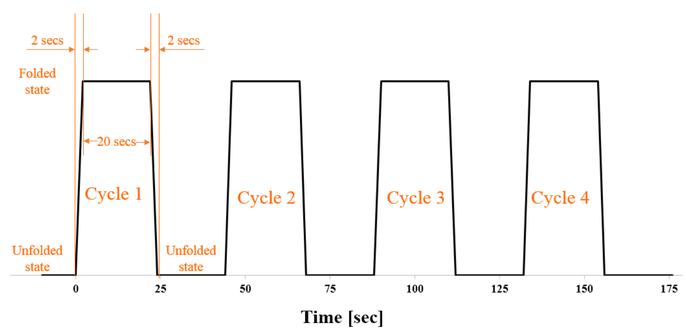

Fig. 5 Fold-unfold cyclic loading used in the simulation to evaluate the performance of the display assembly.

Fig. 6 shows the stress response of the OCA and polycarbonate layer with time. At the end of the first load cycle the peak shear stress in OCA is 0.019 MPa which gradually drops to 0.016 MPa after the 20 seconds of relaxation. The viscoelastic properties of the OCA determines the relaxation rate. Upon unfolding the shear stress changes direction and there is a residual stress of 1.78×10^{-3} MPa in the OCA. This also has an impact on the residual bending stress in the polycarbonate layer which is 3.54×10^{-3} MPa. Over multiple cycles it is observed that the residual stress increases because the assembly does not relax to a stress free state. The rate of

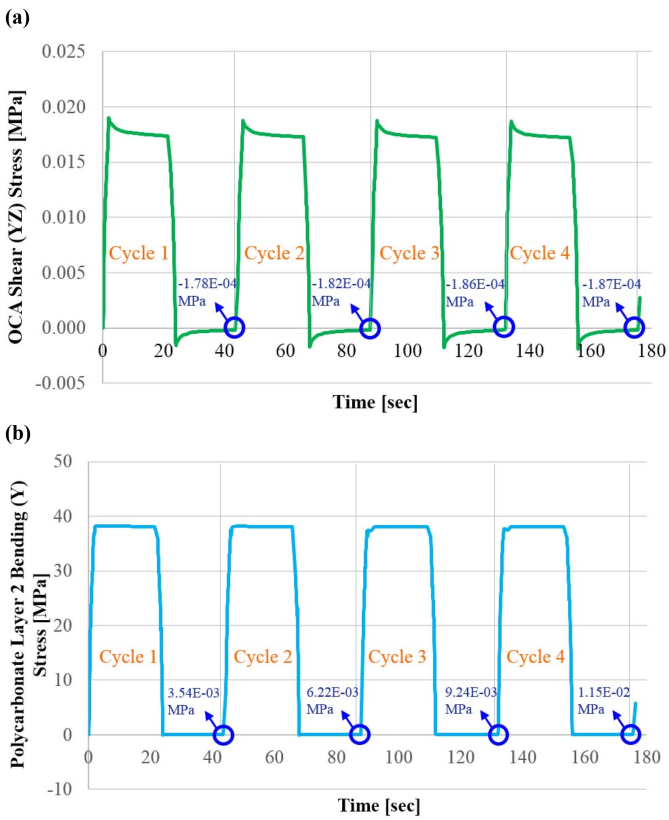

Fig. 6 Stress response of layers during the cyclic loading, (a) OCA shear stress (b) Polycarbonate layer 2 bending stress.

increase of the OCA shear stress is $3\text{x}10^{-6}$ MPa after each cycle and for the polycarbonate layer the bending stress increases at a rate of $3\text{x}10^{-3}$ MPa. Using linear extrapolation of the residual stress, it is expected that after 1000 cycles the residual shear and bending stress would be $5\text{x}10^{-3}$ MPa and 3 MPa in the OCA and polycarbonate layer respectively. This is about 25% & 8% of the observed peak stress in the layers respectively. With the increase in residual stress over large number of cycles we expect to see a degradation of the display's mechanical and optical performance. This can potentially lead to delamination or buckling of the polycarbonate layer.

To further evaluate the impact of the viscoelastic properties of OCA material we have run a cyclic test with a second material model with lower viscous effects. This is a hypothetical material that was created using the same hyperelastic material model as the reference model but with a modified Prony series (Table V). Fig. 7 shows a comparison plot for the storage and loss modulus of the two materials. The loss modulus of the modified material is almost an order lower than that of the reference material.

TABLE V

PRONY CONSTANTS FOR MODIFIED VISCOELASTIC MATERIAL OF OCA

i	Relative Modulus (g_i)	Time Constant (τ_i)
1	0.600	0.001
2	0.250	0.010
3	0.080	0.080
4	0.030	0.200
5	0.035	200.0

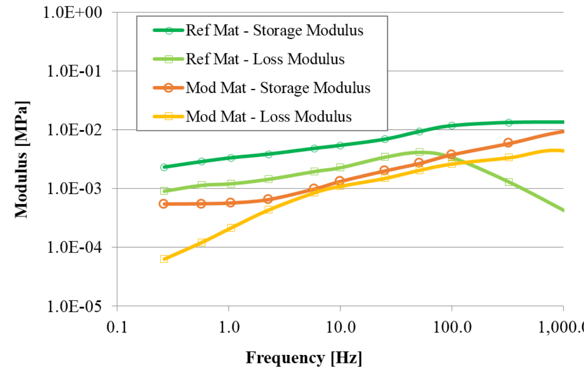

Fig. 7 Comparison of storage and loss modulus of the reference and modified material.

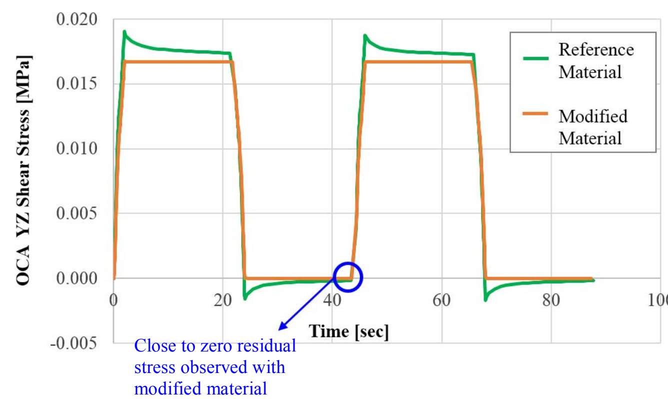

Fig. 9 Comparison of OCA shear stress for the two viscoelastic material models.

Fig. 8 compares the OCA shear stress response over 2 fold-unfold cycles and the modified material has negligible stress relaxation after each cycle. At the end of each cycle the residual stress in the polycarbonate layer is also nearly zero. This again validates our claim that the residual stress is largely an effect of viscous properties of the material and by reducing the viscous behaviour of the material we can considerably reduce the residual stresses.

The results indicate that the choice of OCA material is critical when evaluating the effect of repeated folding over large number of cycles. In this paper we have limited the discussion to a single load profile but the system's response could be very different for other cycling rates and durations. These could be user dependent and therefore it is essential to run additional simulations to evaluate the impact of other load profiles to identify the worst case.

V. CONCLUSIONS

We present an approach to represent the folding of a display assembly using a modified 3-point bend setup in a simulation model. The proposed simulation methodology is validated with two different commercial software and good correlation is seen.

Further the performance of the system under cyclic loading is evaluated by using a viscoelastic material model for the OCA. The residual stress in the OCA is significant and it accumulates over each load cycle. This further affects the other display layers as residual stress build up after each cycle. Any residual stress in the OCA can lead to deteriorated optical performance and mechanical performance of the display. The choice of OCA material is therefore critical for a foldable devices as it is expected to cycle through thousands of folds. We also demonstrate that the viscous properties of the OCA material are critical to its stress relaxation response and its effective residual stress. This is validated with a modified viscoelastic material that has a considerably lower loss modulus. The analysis presented in this paper is for one specific load profile but a foldable device would be used differently by different users. Simulation analysis can be used to evaluate multiple such load profiles to identify the worst case loading and optimize the design and choice of material.

REFERENCES

[1] (2019) Samsung Galaxy Fold – The Official Samsung Galaxy Site. [Online]. Available: https://www.samsung.com/global/galaxy/galaxy-fold/

[2] (2019) HUAWEI Mate X, 5G Smartphone, Foldable Design. [Online]. Available: https://consumer.huawei.com/in/phones/mate-x/

[3] F. Salmon, A. Everaerts, C. Campbell, B. Pennington, B. Erdogan-Haug, and G. Caldwell, "64-1: Modeling the Mechanical Performance of a Foldable Display Panel Bonded by 3m Optically Clear Adhesives," *SID Symposium Digest of Technical Papers* Vol. 48(1), pp938–941, 2017.

[4] Y. Jia, Z. Liu, D. Wu, J. Chen, and H. Meng, "Mechanical simulation of foldable AMOLED panel with a module structure," *Organic Electronics* Vol.65, pp185-192, 2019

[5] Y. Shi, J. A. Rogers, C. Gao, and Y. Huang, "Multiple Neutral Axes in Bending of a Multiple-Layer Beam With Extremely Different Elastic Properties," *ASME. J. Appl. Mech.* Vol. 81 (11), 114501-114501-3 (2014)

[6] S. Li, Y. Su, and R. Li, "Splitting of the neutral mechanical plane depends on the length of the multi-layer structure of flexible electronics," *Proc. R. Soc. A,* Vol. 472, 2016

[7] Y. Niu, S. Liu, J. Chiou, C. Huang, Y. Chiu, M. Lai, and Y. Liu, "Improving the flexibility of AMOLED display through modulating thickness of layer stack structure," *Journal of the Society for Information Display,* Vol. 24(5), 2016.

[8] M. M. Nath and G. Gupta, "Characterization of a Flexible Device using a 3-Point Rolling Test," in *Proc. 2018 International Flexible Electronics Technology Conference (IFETC)*, 2018, p1-5