The influence of the bending mode on the mechanical behavior of AMOLEDs

Bo Wang1, Zeyu Zhang1, Weimei Su1, Wenxin Zhang1, Qiujuan Wang1#, Di Zhang1, Fang Zhang2#

1Hebei Key Laboratory of Flexible Functional Materials, School of Materials Science and Engineering, Hebei University of Science and Technology, Shijiazhuang 050021, China.
2Yungu (Gu’an) Technology Co., Ltd, Langfang, 065500, China.

Corresponding author: Qiujuan Wang (e-mail: wangqiujuan90@126.com), Fang Zhang (e-mail: zhangfang@visionox.com).

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ABSTRACT Structural optimization has always been the main solution for increasing the stability of flexible screens. The bending method used to test a flexible display screen is an important factor in assessing the functionality and practicability of the electronic device. The bending mode of the display screen impacts the screen service life. In this study, 2D simulation models with different bending radii, bending directions, and bending times were constructed in ABAQUS and compared to determine the effects on the flexible screen from changing the stress value, the location of the stress concentration area and the deformation state of the screen under U- and water-drop-shaped bending. The simulation results show that U-shaped bending severely strains the junction between the bent and unbent areas of a model, whereas water-drop-shaped bending can avoid such problems. In addition, the results of multiple bending experiments were used to determine an appropriate reserved length of r=2.1~2.4 mm for a model under water-drop-shaped bending.

INDEX TERMS Simulation, Motion mode, Active matrix organic light-emitting diode (AMOLED)

I. INTRODUCTION

Innovation is important for improving the economic efficiency and portability of display device products. AMOLED display technology has facilitated the gradual replacement of traditional LCD screens with flexible screens in daily life. In recent years, excellent energy consumption performance, display quality and cycle time has resulted in increasingly wide use of AMOLEDs in flexible displays, smart wear and other fields[1–3]. An AMOLED has the advantages of self-luminosity, a wide viewing angle, and high contrast[4]. Compared with a passive OLED, an AMOLED has a higher refresh rate and significantly lower energy consumption and is therefore more suitable for portable electronic devices, which are sensitive to power consumption. In addition, technological development will enable flexible displays, as an important terminal entrance for human-computer interaction, to usher in increased market demand.

The structural stability and cycle life of the AMOLED flexible screen have become important metrics of meeting considerations of portability and economy. There are significant differences in the mechanical properties of the functional layers of a flexible screen[5]. To balance the forces on a flexible screen, the principle of neutral layer fracture was proposed, whereby a buffer layer is inserted into a functional layer to disperse the force concentrated therein[6]. At present, the main constituent material of a
neutral layer is an optical adhesive material (OCA) with both hyperelasticity and viscoelasticity[7]. Jia et al. used fitting methods to determine analysis formulas for the hyperelasticity and viscoelasticity of an OCA[8]. The neutral layer area is an important consideration for an AMOLED flexible screen, along with the components of the functional layer, including the protective cover, polarizer, touch screen, OLED and back plate film. Modifying the PI layer in the functional layer and constructing a hollow structure can significantly improve screen stability[8, 9]. Increasing the number of neutral layers and changing the layer thickness can deflect the maximum force on the screen away from the functional layer and is therefore an important means of optimizing the structure of the flexible screen[10,11]. In addition to changing the statics of the screen via the structure and composition, the dynamic movement of the screen can be changed by considering a combination of mechanical data obtained from simulations and actual tests on a screen to determine various characteristics of the screen. The movement mode of a screen considerably influences the recyclability of a flexible screen.

Currently, the U-shaped bending method is generally used for simulation[10–14]. Completely overlapping the two sides of a screen many times to perform U-shaped bending leaves creases in the screen[15, 16]. However, using water droplets for bending changes the curve bending trajectory and leaves an unbent area, which helps avoid screen creasing. This novel bending method can extend screen service life and facilitates the design of non-crease flexible display screens. Using water droplets to bend a screen reduces the linear distance between the bent and unbent areas, and the reduced volume of the folded screen improves portability.

In this work, ABAQUS is applied to establish U- and drop-shaped multiple bending methods on the stress and strain of a flexible panel. Unlike the commonly used single bending model, the simulation results of multiple bending intuitively show that the bending radius directly affects the final screen state after repeated bending. Moreover, not just the maximum stress which is normally used, the recovery degree of the panel group has been an important factor to measure the bending situation in this article and make the results of simulation more reliable.

II. DESCRIPTION OF THE MODE

A. STRUCTURE OF THE SCREEN GROUP

A simulation was performed to analyze the bending of an AMOLED flexible screen, for which the finite element analysis method was used to establish a 2D plane model in ABAQUS. A rectangle with a total length of 15 mm was set as the longitudinal plane of the flexible screen, of which the material properties are listed in Table 1. The 2D model adopted tetrahedral mesh to avoid shear locking, and most of films had been divided into three layers. The element type was CPS4R. The maximal difference in stress distributions along the bending symmetry plane only amounts to 2.6 %, compared to original mesh method. The relative error was far from 5%, which means the result was reliable.

| Panel Component          | Material | Density (Kg/m³) | Young’s Modulus(GPa) |
|--------------------------|----------|-----------------|----------------------|
| Cover Film               | PI       | 1490            | 6                    |
| Optical clear adhesive   | Acrylic  | 1180            | 0.026                |
| Polarizer (POL)          | PVA      | 1290            | 4                    |
| Touch panel (TP)         | PI       | 1490            | 3                    |
| OLED                     | PI       | 1490            | 16                   |
| Back Plate Film          | PI       | 1490            | 6                    |

B. MATERIAL PROPERTIES OF OCA

An optically clear adhesive (OCA) is a special substrate-free double-sided adhesive with optical transparency that is often used as a buffer layer in flexible screen panels. Application of an OCA reduces light loss of the screen, which improves the contrast and therefore the image quality of the screen. This unique adhesive layer improves the connection strength between different functional layers and makes the screen flatter. However, the OCA differs from the materials used in the functional layer in possessing both
superelasticity and viscoelasticity. Therefore, to perform an accurate simulation experiment, suitable hyperelastic and viscoelastic models must be introduced to define the OCA attributes.

A uniaxial tensile test was performed to obtain tensile strength data for the OCA. The experimental data were fitted in ABAQUS, and the results were used to select the Yeoh model (given below) to characterize the hyperelasticity of the material for a simulation experiment.

\[ U = \sum_{i=1}^{n} C_i (I_1 - 3)^i + \sum_{k=2}^{n} \frac{1}{k} (I_1 - 1)^k \]  

In the equation above, \( J \) is the ratio of the volume after deformation to that before deformation. \( I_1 \) is the first strain tensor invariant. \( N, C_i \) and \( D_i \) are input parameters.

The viscoelastic behavior of the OCA was determined by the time-varying shear modulus and bulk modulus. These moduli were expressed using the Prony model in the simulation[20].

\[ G(t) = 1 - \sum_{i=1}^{n} g_i^P [1 - \exp \left( -\frac{t}{\tau_i} \right)] \]  

\[ \frac{K(t)}{K_0} = 1 - \sum_{i=1}^{n} k_i^P [1 - \exp \left( -\frac{t}{\tau_i} \right)] \]  

\( G_0 \) and \( K_0 \) denote the instantaneous shear and bulk moduli determined by the instantaneous elastic modulus. \( g_i^P \) and \( k_i^P \) are Prony constants, and \( \tau_i \) is a state variable that controls the stress relaxation.

**C. THICKNESS OF OCA**

To develop a flexible panel with a suitable thickness and performance, four simulation schemes with different thicknesses were proposed, as shown in Table 2. The four schemes were used to simulate U-shaped bending with an inner bending radius of 2.5 mm, and the optimal structure was selected based on the strain changes of the film layer.

The optimal model structure was determined by simulating four structural schemes with different OCA layer thicknesses. As the strains in the polarizer layer (POL) and the touch screen layer (TP) were less than 0.1, as shown in Fig. 1, the strains in the cover glass layer (cover film), OLED layer, and backplane film (BPF) were carefully observed to select the optimal structure. The model structure for Scheme 1 had relatively small strains in the three functional layers, but the mesh deformation was found to be relatively large during the simulation process. Although the stress on the cover layer for Scheme 2 was quite high, there was no discernible strain in the OLED and backplane layers, and the formed module was relatively thin but able to produce an ideal simulation result.

**TABLE 2. FOUR MODULE SIMULATION STRUCTURE SCHEMES WITH DIFFERENT OCA THICKNESS**

| Material | Option1 | Option2 | Option3 | Option4 |
|----------|---------|---------|---------|---------|
| Cover    | 90      | 90      | 90      | 90      |
| Film     |         |         |         |         |
| OCA      | 50      | 75      | 75      | 75      |
| POL      | 47      | 47      | 47      | 47      |
| OCA      | 50      | 50      | 75      | 75      |
| TP       | 25      | 25      | 25      | 25      |
| OLED     | 31.5    | 31.5    | 31.5    | 31.5    |
| OCA      | 50      | 50      | 50      | 75      |
| BPF      | 90      | 90      | 90      | 90      |

**FIGURE 1. Comparison of strains in modules with different OCA layer thicknesses**

**D. BENDING METHOD**

Two bending modes, U-shaped bending and water-drop-shaped bending were simulated, as shown in Fig. 2. In the U-shaped bending mode, the reserved length of the bending area was \( l = \pi*R \), and the bending slip was calculated as \( \Delta l = (\pi-1)*R/2 \). For drop-shaped bending, the length of the reserved area was also \( l = \pi*R \), but the slip was \( \Delta l = \pi*R/2 \).

During the first five seconds, the shaded part of panel rotated clockwise and counterclockwise around the reference point at 0.314 rad/s, while moving upwards at \( (\pi-1)*R/2 \) mm in U-shaped bending or \( \pi*R/2 \) mm in drop-shaped bending, and then back to place for 5 seconds. The whole process would be repeated for 10 times. Furthermore, each analysis step was calculated from 1E-03, the minimum increment size was 1E-15.
III. RESULTS AND DISCUSSIONS

A. STRAIN CHANGES AT THE JUNCTION

In the case of U-shaped bending, the maximum force on the screen is exerted at the junction of the bending area and the undeformed area, as shown in Fig. 3 (a). In this set of simulations, the junctions create by the two different bending methods, U-shaped and drop-shaped bending, are selected as reference points (as shown in Fig. 3 (a), (b)). The magnitude of the stress and strain of the screen for different bending radii has been determined. The force exerts on the junction is significantly lower under water-drop-shaped bending than under U-shaped bending, as shown in Fig. 3 (c). The strain at the junction of the screen is correspondingly reduced, as shown in Fig. 3 (d). According to Table 3, the accurate stress and strain data obtained from optimizing the efficiency for the water-drop-bending mode are 16.74% and 44.17%, respectively. To simulate water-drop bending, it is important to select a suitable reserved length that meets the conditions of a small stress and a stable fluctuation range. Under a single bend, a reserved length for water-drop-shaped bending of \( R \leq 2.4 \) mm improves the screen mechanical characteristics. Although the drop-shaped bending method reduces the load at the junction and reduces the strain on the joint compared to U-shaped bending, the maximum strain of the back plate is much higher, as shown in Fig. 3 (e).

Therefore, the state of the backplane should be carefully observed when studying drop-shaped bending.

![Diagram of U-shaped bending and drop-shaped bending](image-url)

**FIGURE 2.** Schematic diagram of U-shaped bending and drop-shaped bending.

![Effect of the bending method on the deformation of the screen](image-url)

**FIGURE 3.** Effect of the bending method on the deformation of the screen: (a) U-shape; (b) Water drop shape; Effect of the bending radius on the mechanical properties of the joint in different bending method: (c) the maximum stress; (d) the maximum strain; (e) Effect of the bending radius on the maximum strain of the screen in different bending method.

The creation of a drop-shaped inner bending area disperses the concentrated stress over the entire inner bending area, weakens the strain at the original junction and produces a good buffering effect. Decreasing the bending radius makes the buffering effect of the inner bending area more noticeable. The advantage of drop-shaped bending lies not only in the good stress dispersion effect on the outer bending area but also in the effective reduction of strain in the bending area of the panel assembly.

| R (mm) | Stress (MPa) | Strain (%) |
|-------|-------------|------------|
| 1.6   | 0.12        | 0.5        |
| 2.0   | 0.08        | 0.3        |
| 2.4   | 0.06        | 0.1        |
| 2.8   | 0.04        | 0.05       |

**TABLE 3.**
THE INFLUENCE OF TWO BENDING STATES ON THE MECHANICAL CHANGES OF THE JUNCTION

|          | Δstress (MPa) | Δstrain (%) |
|----------|---------------|-------------|
| U-shape  | 580           | 0.01965     |
| Water drop | 483           | 0.01097     |

B. THE INFLUENCE OF BENDING DIRECTION

In water-drop-shaped bending, the central region of the outward bending area of the screen is the area with the maximum strain. As the strain at the junction is not discernible (as shown in Fig. 4 (a)), the overall strain of the module must be determined by carefully observing the changes in the central area of the screen. As there is no obvious difference in the stress and strain of the screen when folded inwards and outwards, the analysis should focus on the change trend for a bending direction. As shown in Fig. 4 (a), the maximum strain of the module gradually decreases as the radius increases. The overall stress change of the panel exhibited the same trend, although the stress dropped sharply in the R=1.5~2.0 mm range, as shown in Fig. 4 (b). Therefore, the ideal bending radius is R>2.0 mm.

When the screen is bent outwards, the considerably different material properties of the back plate and cover glass result in no discernible transmission of the strain for each layer of the panel; the maximum stress and strain values of the panel are both small, and there is no discernible change in the trends for these variables. When the screen is bent inwards, the stretching and squeezing trend for each film layer changes, and the overall force on the screen also changes significantly. Thus, the material properties of each film layer need to be considered when selecting a bending direction. The harder the module layer is, the more effective the reduction is in the portion of the stress changes caused by bending, and stress concentration will occur near the relatively soft functional layer. The position of the neutral layer and the number of layers in the stress concentration area can be adjusted. The same goal can be achieved by changing the bending mode of the screen.

C. MULTIPLE BENDS

The continuous strain results for a screen that has been bent ten times using different bending radii and bending methods are used to estimate the damage degree for the screen. As shown in Fig. 5 (d) and (e), ten repeated bending cycles for the screen produce wrinkles in unexpected areas. Under U-shaped bending, the largest deformation is concentrated in the junction area between the cover film and the back plate. However, under water-drop-shaped bending, the OCA layer in the middle of the junction area exhibits the largest deformation. Therefore, under water-drop-shaped bending, the optical clear adhesive layer bears the highest stress. At R=2.4 mm, the screen undergoes a large deformation after ten water drop bends, which is not conducive to long-term screen use (as shown in Fig. 5 (a)). Bending the screen multiple times, as shown in Fig. 5 (c), also changes the trend in the strain for the area of maximum strain of the bent screen. This result shows that the wrinkles of the screen group from the bending cycles were superimposed and increasing the bending radius affected the trend in the extension of the maximum strain area of the bent screen. Under U-shaped bending, the back plate of the screen bears the highest stress, and exhibits the most noticeable deformation after multiple bending cycles. However,
changing the bending method to water-drop-shaped bending results in a significant reduction of the strain at the junction of the backplane, and the backplane protrudes upward as the bending radius increases, as shown in Fig. 5 (d).

![Graph](image)

**FIGURE 5.** (a) Effect of the bending radius and the number of bending on the maximum strain of the back plate layer in water drop shaped bending; (b) Effect of the bending radius and the number of bending on the maximum strain of the back plate layer and cover film in Water drop shaped bending; (c) The influence of different bending states on the maximum strain of the back plate layer; Schematic diagram of the final state of the screen group after ten bends (d) U shape; (e) Water drop shape.

Under water-drop-shaped bending, the adhesive layer is squeezed into the middle area between the outer and inner bending zones due to the influence of the stress directed at both ends. Therefore, the screen group bulges on both sides of the central area after multiple bends, which does not occur under U-shaped bending. In the following experiment, the panel presents the same shape after 200,000 drop-shaped bending, as shown in Fig 6 (d). When the bending radius increases to 3 mm, the layers near cover film will be peeled off, as Fig 6 (b) and (c) shown. Furthermore, the noticeable crease has been left after 100,000 times drop-shaped bending, according to Fig 6 (a). However, reducing the bending radius weakens bulging. Therefore, a small bending radius is more appropriate for simulation design of water-drop-shaped bending. Changing the bending radius also affects the area over which the maximum stress is concentrated, that is,
decreasing the bending radius reduces the area over which the force is concentrated. Therefore, if a small bending radius is used in a module design, the thickness of each neutral layer needs to be further optimized.

![Drop-shaped bending](image)

**FIGURE 6.** (a) The screen group has been folded after 100,000 times drop-shaped bending; The junction part in (b) U-shaped bending state and (c) in drop-shaped bending state after 100,000 times folding; (d) The screen group has been folded after 200,000 times drop-shaped bending.

**IV. CONCLUSIONS**

A simulation experiment was performed using a 2D model constructed in ABAQUS, the results of the simulation experiments showed that that an appropriate increase in the OCA thickness reduces the strain in the functional layer. However, an OCA layer with a thickness over 175μm would significantly squeeze the functional layer, and the increased film pressure would hinder strain reduction.

The drop-shape bending method significantly reduced the pressure in the boundary area between the unbent and bent areas. However, the water-drop-shaped bending method considerably increased the stress in the central area of the screen compared to that produced under U-shaped bending. The study on the influence of the reserved length of the bending area on the strain showed that the optimal bending effect was obtained for a bending radius between 2.1 and 2.4 mm, the main force-bearing area of the screen lied within the neutral layer. According to the location of maximum force area, optimizing the mechanical properties of the cover glass may become a good choice to improve the screen life. However, there is a tradeoff between a low stiffness and reducing screen scratches for practical applications, which should be an important consideration for future optimization studies.

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Bo Wang received the Ph.D. degree from the Northeastern University, in 2009. He is currently a professor with the school of Materials Science and Engineering, Hebei University of Science and Technology. His current research interests include the Mechanical Properties of Flexible AMOLED, optimization techniques and data simulation.

Zeyu Zhang is studying at Hebei University of Science and Technology. Since 2020, she has involved in the research and development of flexible folding screen and full-screen display terminal manufacturing technology and demonstration application projects. Her research interest cover the simulation and analysis of flexible AMOLED mechanics.

Weiwei Su is a graduate student at Hebei University of Science and Technology. Since 2020, he has involved in the research and development of flexible folding screen and full-screen display terminal manufacturing technology and demonstration application projects. Committed to the research and development of flexible screen simulation.

Wenxin Zhang is a graduate student at Hebei University of Science and Technology. Since 2020, she has involved in the research and development of flexible folding screen and full-screen display terminal manufacturing technology and demonstration application projects. Her research interest is the simulation and analysis of flexible AMOLED mechanics.

Qiuju Wang received the Ph.D. degree in Materials Science and Engineering from Beijing University of Science and Technology, in 2015, spend three years as a postdoctoral at South China University of Technology from 2015 to 2018. She has been working at School of Materials Science and Engineering in Hebei University of Science and Technology from 2018. Her research interest focuses on mechanical simulation of thin film encapsulation for flexible AMOLED.

Di Zhang received the Ph.D. degree from the Northeastern University, in 2012. He is currently an Associate professor in School of Materials Science and Engineering, Hebei University of Science and Technology.

Fang Zhang is currently a CAE researcher in Yungu (Gu’an) Technology Co., Ltd. His main research area is mechanical simulation of flexible AMOLED.