Dynamic fast fracture of smartphone screens

I A Magomedov$^1$, I V Orlova$^2$, O I Lisichko$^2$, S Kh Alikhadzhiev$^3$

$^1$Chechen State University, 32 Sheripova Street, Grozny, 634050, Russia
$^2$Irkutsk National Research Technical University, 83, Lermontov str., Irkutsk, 664074, Russia
$^3$Department of Physical and Mathematical Research, Laboratory of Experimental Physics, 21 Staropromyslovskoe, Grozny, 364051, Russia

E-mail: ismwork@mail.ru

Abstract. This thesis is focused on comparing fast fracture of two screens of smartphones (Apple 5 and Samsung alpha). The analysis is done using the novel method, which is eXtended Finite Element Method (XFEM) and a cohesive element (CE) using software Code_Aster and Salome Meca. An apple screen (Sapphire) illustrated high resistance to fracture, while Samsung (Gorilla Glass) fractured with applied force is smaller than the one applied to Apple (Sapphire). However, Gorilla Glass wins in crack propagation by demonstrating better performance. We worked out that the size of screen also influenced fracture. Gc influence on crack propagation was observed. The results illustrated that by increasing Gc the crack propagation will be reduced and vice versa. In addition Gc change will have more influence when applied force is smaller. Influence of other cracks on initiation new crack was also analysed. The results showed that the initial cracks might increase displacement of deformed body, but reduce crack propagation. The results also showed that Gorilla Glass tends to be deformed more if compared to Sapphire.

1. Introduction
In developed countries application of glass is vast beginning from large objects to small particles. Glass is widely utilized in the fields of: architecture, automotive industry or in the high-tech and the analogous fields, which are the most investigated by researchers [1]. Attention to so called specialty glasses is due to the demand of modification of glass property as application of those are increasing annually [2]. A smartphone is one of the devises, which uses glass that usually covers front area (display). It allows the owner of smartphone to visualize and use it as input function. In the market of smartphones Apple and Samsung shares place of bestselling companies of smartphones in the last years [3]. There are two type of well-known glasses utilized by Apple and Samsung: Sapphire and Gorilla glass respectively. Sapphire naturally comes in different colors, but color-less sapphire is used as it better fits for smartphone. However, sapphire is brittle and suitable for watch covering and camera lenses as smartphones have a larger area of the screen. Gorilla glass is not as strong and scratch resistant as Sapphire, but approximately three times cheaper and have almost the same properties as Sapphire. Table 1 represents properties of both materials.

There are different methods to investigate crack propagation in the smartphone screen: theoretical, experimental and finite element approaches. The experimental methods are most reliable due to the providence of real measured data and reliability of results. However because of the cost and the time
implications of experimental method, the researchers use the FE method to simulate crack propagation which has capability to work with huge numbers of degrees of freedoms representing crack propagation accurately [4]. Despite of a number of FE method advantages, Finite element method will always be used as a design predictive tool and there would always be need for experimental testing to validate and confirm the FE models. In this project, code-aster software will be used to design and analyse fast fracture of smartphone screens.

2. Materials and methods

Two approaches of modelling can be considered when dealing with the dynamic response of material to fracture. Let us begin with the wave equation using computational fluid dynamics to solve the transient dynamics. The second one is to use Finite element method with the extension of including kinetic energy. In this work, dynamic fracture will be modelled using a combination of extended finite element method (XFEM) and cohesive elements.

As the name suggests the extended finite element method (XEFM) is extended version of the classic finite element method (FEM), where it has a significant level of mesh dependency. The extended finite element method was created to solve the problems that arise from localized features, which cannot be solved by finite element method, as it requires update of the mesh as crack propagates. Therefore, XFEM is used to overcome the mesh dependency and cohesive element to deal with the non-linearity of the problem and it is used to represent material physics closely. XFEM deals with the mesh dependency through enriching nodes utilising differential equations figure 1. Specifically for crack growth XFEM is used to allow propagation using the standard mesh in the arbitrary direction and through the standard elements [5].

![Figure 1. Enriched nodes with the discontinuous function:](image)

\[ u(x) = \sum_i N_i(x) u_i + \sum_i M_i(x) a_i ; \]
\[ \sum_i N_i(x) = 1. \]

The basic formulation and approach of the extended finite element method can be visualized from equations above. Here \( u(x) \) is the suitable function for one element, \( N_i(x) \) is the standard finite element function for node \( i \), while \( u_i \) is unknown part and \( M_i \) is the local enrichment of node \( i \) and \( a_i \) is the unidentified enrichment at node \( i \). Linear elastic fracture mechanics (LEFM) is a powerful tool when dealing with a linear problem with crack presence and ignorance of the plastic zone near the crack tip etc. However when it comes to a nonlinearity of the crack tip region, in which plastic zone or microstructure of ductile metals and cementitious materials respectively is comparably larger than the dimensions of the cracked body. Moreover, for brittle material, the need for initial crack is necessary for the application of LEFM to work. Here is a cohesive zone model which can deal with the plastic zone ahead of the crack. In addition, the cohesive zone model can effectively predict the behaviour of the uncracked body (structure) [6]. Extended finite element modelling with cohesive elements (XFEMCM) was created (designed) to combine the advantages of the both approaches. Combined together they bond powerful tool to investigate the dynamic propagation of the initial crack in the 2D
brick geometry and capture effects of strain wave propagation, which are resulting in stress magnification and capable of initiating second crack propagation as an outcome of first. (XCSM) works within Code-Aster having at the beginning of the rigid cohesive zone and computing the possible crack propagation region. For the following thesis material properties for two screens will be used, which are Sapphire and Gorilla Glass (IPhone 5 and Samsung Galaxy Alpha respectively). All the values of the material property can be found from published date. However, two of the values of tensile yield strength and strain energy release rate for both screens were calculated manually.

Table 1. Properties of two materials

| Material properties          | Sapphire | Gorilla Glass |
|-----------------------------|----------|---------------|
| Young’s modulus (GPa)       | 345      | 71.1          |
| Passion’s ratio             | 0.25     | 0.21          |
| Density (kg/mm$^3$)         | 3.97*10^{-6} | 2.42*10^{-6} |
| Vickers hardness (kg/mm$^2$)| 2200     | 649           |
| Fracture toughness (MPa$\sqrt{m}$) | 2.3      | 0.68          |
| Tensile yield strength (MPa)| 7333.3   | 2163.3        |
| Strain energy release rate  | 14.375   | 6.216         |

3. Results

Applied Range of Forces. The following paragraphs will illustrate results of two structures under different forces. The x coordinate should be at the mid of the plane to allow the crack to be propagated. It is because the code is programmed to initiate a crack along x coordinate. The forces applied were increased up to the point where the structure will break. The structure under these forces will fracture and will have no time for crack propagation. It is due to the stress concentration at the middle of the structure, which are generated by the chosen boundary condition. Therefore there will be an immediate crack going through. It was obvious that the structure with higher Gc will resist to break more than the one with lower value. Analysis was done to see if the results from the software were following the tendency and see how reliable they are. By looking into the material properties (MP) Sapphire has higher Gc and will require more force to break. For model of Apple (IPhone 5) the force required to fracture was higher than for Samsung’s model. The results illustrated that there will be no fracture bellow roughly 7.5 N. The point of deformation will increase over the time as force is acting on the structure, due to analysis being dynamic, but no fracture will occur below roughly 7.5 N. As the force applied was increased to 7.5 N and more the analysed structure illustrated that fracture will be achieved. Samsung model illustrated different results than Apple model. The results showed that force required to fracture the structure was low compared to model of IPhone. Minimum force required to fracture the structure of Samsung was roughly 4.5 N. However, as force was decreased to 4 N and below the results illustrated no crack initiation or fracture. It can be said that above the value of 4.5 N the structure will break.

Influence of Gc on crack propagation. The next paragraph will look at influence of Gc on Crack initiation or propagation. The following boundary conditions (forces) were applied to the structures of two smartphones. Partition was added to the structure at the left side. It was introduced to avoid rapid fracture. The force values 9 and 5 N were used for the following analysis with different Gc. To measure the crack propagating more precisely, the tool ‘rule’ was used. Table 2 below gives the crack propagation values for different Gc with two forces. Shear and dilation waves were calculated. For different Gc the shear and dilation waves will be the same, but different for different material properties and sizes. It is
due to the wave speeds in the geometry are linked to the bulk material density (viscosity), therefore they will be the same.

| Material properties | \( G_c \) (Jm\(^2\)) | Force (N) | Crack length (mm) | Difference between shear and dilation waves (s\(\times10^6\)) |
|---------------------|-----------------|-----------|-----------------|---------------------------------|
| Sapphire            | 1.2160          | 9         | 26.8            | 9                               |
|                     | 3.2160          |           | 26.6            |                                 |
|                     | 6.2160          |           | 26.3            |                                 |
|                     | 16.216          |           | 25.4            |                                 |
|                     | 1.2160          | 5         | 16.4            | 9                               |
|                     | 3.2160          |           | 15.9            |                                 |
|                     | 6.2160          |           | 15.0            |                                 |
|                     | 16.216          |           | 14.2            |                                 |
| Gorilla Glass       | 1.2160          | 9         | 25.90           | 4                               |
|                     | 6.2160          |           | 25.17           |                                 |
|                     | 1.2160          | 5         | 16.6            | 4                               |
|                     | 6.2160          |           | 15.8            |                                 |

**Figure 2.** Four Different Deformed Bodies with Sapphire and Gorilla Glass Material Properties

Multiple crack or initial notches. This analysis was done to see how the other cracks (notches) have influenced the initiation and propagation of a new crack in terms of displacement, with the constant force applied. It illustrates four similar structures with different notches. Figure 2 illustrates the deformed bodies after analysis with material properties of Sapphire and Gorilla Glass respectively. The
left and right tops are deformed bodies of original and two parallel notched respectively. The left and right bottoms are deformed bodies of side notch and back notch respectively. The following figures 7 and 8 represent displacement of the four deformed bodies over a time.

For the two structures under different forces we illustrated different behaviours. As it was expected, Apple structure showed that it requires more force to be broken than the structure of Samsung due to its higher Gc. Looking from percentages perspectives it will be approximately 67% more of (3 N) force required than for the structure of Samsung. The analysis was performed to see the tendency of the results or somehow to validate the results from the software. In other words Gc of Apple structure was much higher which will result in higher force to break or initiate any crack. The results illustrated this tendency, which leads not to a full validation of all results.

It was also found that with the smaller size the structure resists to fracture. With the material properties of Samsung applied to Apple (124x59mm) the results illustrated better suitability than for its own size (Samsung 132x66). It showed that Gorilla Glass will fracture after 4.5 N, while Apple screen with the Samsung properties will break between 4.6 – 5 N. One can say that screen size plays a big part in fracture mechanics. Due to the time consuming with each analysis it was difficult to catch the exact force required to break the structure. Therefore, the values of forces applied have rounded numbers and big jumps (of 0.4 N max and 0.1 N min). In addition, material properties of Apple were not applied to the Samsung structure. The results might have the same tendency.

By investigating the existing crack in the structure of both screens of smartphones the results were collected. As previous discussed it was said that uncracked structure of Sapphire required more force to be fractured than Gorilla Glass. However, it showed different tendency when analysed with initial crack in it. The results of Sapphire glass illustrated that crack propagation will go further than in Gorilla Glass with the same size and applied force. With the initial crack length of 17mm, the crack in Sapphire propagated 13mm more and stopped at 30 mm. Gorilla Glass illustrated only 10mm propagation from the initial crack and stopped at 27. Sapphire crack propagated 3mm longer than that in Gorilla Glass. It can be said that Sapphire is harder to brake, but one fractured its weaker than that of Gorilla Glass. To collect more precise results the two structures of two smartphones were built as with real dimensions. The Gc effect on crack initiation or propagation was investigated. The results were gathered from different aspects by changing the Gc. The results illustrated that Gc has effect on crack propagation. By observing the table 2 its clear that by reducing Gc the crack length will increase. It was also observed that with the larger force the Gc effect on crack propagation is small. For instance, when force applied was 9 N we observed the increase in length of crack being around 0.2 - 0.5 mm with different Gc. However, when force changed to 5 N the increase was notable around 1 – 1.2 mm. The results also showed that Gc has no influence on the Shear and dilation waves. Due to the wave speeds in the geometry there is linked viscosity. By observing the result, it can be said that by increasing the force, the difference between shear and dilation waves will reduce. When Gorilla Glass MP was applied to two geometries, it showed that it will required small force to fracture or initiate the crack as was discussed previously.

Geometries with initial notches were investigated to see the influence on crack initiation in terms of displacement. The results illustrated for both material properties that more influence will come from the two parallel notches, which will have around double displacement if compared with original. Side and back notches will have almost the same displacement as original, with a noticeable increase in a displacement. The small influence will be by having back notch and a bit larger by side notch. The tendency will be the same for both material properties. However, with larger displacement there will be smaller crack length. It was observed that for two parallel notches there will be 46.5 mm and 44.9 mm propagation for Sapphire and Gorilla Glass respectively. But for original this is 53.48mm and 52.8mm and S and GG, respectively. In the second place there was side notch with 51.3 mm for Sapphire and 50.8 mm for GG. And the grater propagation will occur with back notch, which is 53.6 mm for S and 52.9 mm for GG. It was also observed that Gorilla Glass to be compared with Sapphire will have more displacement and smaller crack propagation.
4. Conclusion
Dynamic fast fracture was investigated using a novel method. This work analyzed different aspects that might have influence on the structure in terms of crack propagations. The results illustrated defined correlations with the experimental work.

References
[1] Dubiel M, Haug J, Kruth H, Hofmeister H, Schicke K-D 2008 Ag/Na ion exchange in soda-lime glasses and the formation of small Ag nanoparticles. Materials science & engineering. B. Solid-state materials for advanced technology 149(2) 146.
[2] Wondraczek L, Mauro J C, Eckert J, Kühn U, Horbach J, Deubener J, Rouxel T 2011 Towards Ultrastrong Glasses. Advanced Materials 23(39) 4578-4586
[3] Lunden I 2016 Led By iPhone 6, Apple Passed Samsung In Q4 Smartphone Sales. 1.9B Mobiles Sold Overall In 2014. TechCrunch. Retrieved from: http://techcrunch.com/2015/03/03/led-by-iphone-6-apple-passed-samsung-in-q4-smartphone-sales-1-9b-mobiles-sold-overall-in-2014/#.fdcilh1:8exz
[4] Nouby M, Srinivasan K 2015 Simulation of the structural modifications, Part D: Journal of Automobile Engineering 225(5) 653-672
[5] Crump T, Ferté G, Mummery P 2015 Dynamic fracture effects on remote stress amplification in agr graphite bricks. Smirt-23 80
[6] Elices M, Guinea G, Gómez J, Planas J 2002 The cohesive zone model: advantages, limitations and challenges. Engineering Fracture Mechanics 69(2) 137-163
[7] Li J, Huang, Q, Ren X 2013 Dynamic Initiation and Propagation of Multiple Cracks in Brittle Materials. Materials 6(8) 3241-3253
[8] Guynn E G, Bradley W L, Elber W 1989 Micromechanics of Compression Failures in Open Hole Composite Laminates. ASTM STP 1012 (American Society for Testing and Materials, Philadelphia, PA)
[9] Roberts D K, Wells A A 1954 The Velocity of Brittle Fracture. Engineering 178 820–821
[10] Freund L B 1976 Dynamic Crack Propagation.” The Mechanics of Fracture, American Society of Mechanical Engineers (New York)
[11] Gdoutos E E 2006 Fracture Mechanics: An Introduction, volume 123 of Solid mechanics and its applications. (Springer)
[12] Ershov D Y, Zlotnikov E G, Koboyankwe L E 2017 Dynamic processes in technological systems of machining and the nature of their origin. IOP Conference Series: Earth and Environmental Science 87(8) 082016
[13] Solovev S V, Kryl’tsov S B, Voytyuk I N 2018 Static load characteristics consideration for determination of transmission line power capacity. Proceedings of the 2018 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering, EiConRus 2018, 2018-Janua
[14] Maksarov V V, Khalimonenko A D 2018 Quality assurance during milling of precision elements of machines components with ceramic cutting tools. International Review of Mechanical Engineering 12(5) 437 – 441
[15] Khalimonenko A D, Pompeev K P, Timofeev D Yu 2019 Dimensional analysis of the manufacturing processes of axisymmetric parts. IOP Conference Series: Materials Science and Engineering 560 (1) 012144