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Numerical Investigation into the Effect of Laminated Casing on the Impact Resistance of Smartphone Screens

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ABSTRACT

A survey shows that most smartphones damages are due to frequent falls, owing to their small nature coupled with poor handling. This results in cracked screens to broken parts, to total damage. Although advancements like the gorilla glass which claims to be both scratch and crack resistant have been successful. However, this has only reduced screen damage. The overall effect of high and low-velocity impact on phones has not been reduced. Hence, this study focuses on the impact performance of laminated cellphone casing. The laminate is achieved through force fit of different layers of the lamina. Four laminated scenarios are examined. The impact analyses of single, double, triple, and quadplex layers of the laminate are studied within a drop height of 0.5m - 2.5m and a step size of 0.5m. Various polycarbonate layers of the phone casing are captured as an elastoplastic material model. The assembled model of the phone casing with the screen is achieved through Autodesk Inventor® while Solidworks® drop test module is employed to simulate the different impact conditions. Results from the stress, strain energy, and displacement responses reveal that the number of laminate layers relates inversely to the effect of impact load on the phone screen. The computational outcomes of the present study demonstrate a reasonable agreement with laboratory evidence recorded in the literature.

1. Introduction

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The digital age resulting from the advancements in technology has enabled the evolution of supercomputers [1] that is being loaded into small devices, smartphones [2] which are capable of several functionalities. The major challenge faced by these new portable devices is dropping due to the miniature size of these devices, coupled with poor handling by its owners. According to a survey, a large proportion of the total number of smartphones is damaged due to falls [3]. From cracked screens to broken parts, to overall damage, which has been a constant occurrence. Although advancements have been made in curtailing this trend, for example, the gorilla glass [4], Asahi Glass [5] and Schott AG Xensation [6] which claim to be both scratch and crack resistant have been successful. However, these have only reduced screen damage. Synthetic sapphire [7] is being eyed for phones, which will be lovely for resisting minor scrapes and dings, but the results on impact have been discouraging. This has necessitated the study into the configuration of a cellphone casing as a sandwiched laminated structure.

The application domain of sandwich structures nowadays is where lightweight materials with enhancing flexural stiffness and in-plane are essential. These composite materials are being used in several applications within the aerospace, marine and automotive industries because they have advantageous properties such as lightweight, corrosion resistance, thermal and electrical insulation. The configurations of sandwich system materials are unlimited with a wide range of skin and core materials. To select the right materials, some factors should be taken into accounts such as strength, stiffness, adhesive performance, environmental behaviour, and economic availability.

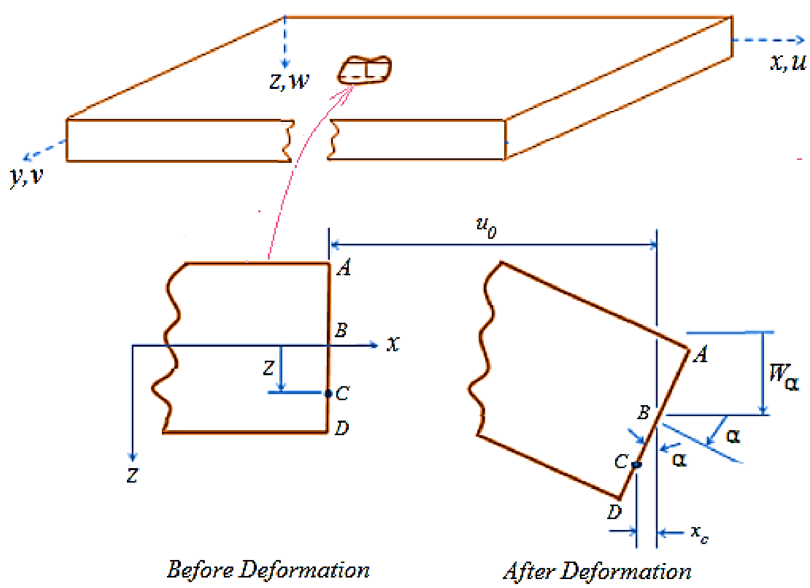

Fig. 1. Laminate Deformation in x-y Plane.

Lamination is the practice of multiple layers production of material to achieve improved strength, stability, sound insulation and appearance of the composite material [8]. The permanent assemblage of a body employing either adhesives, pressure, heat or welding is known to be a laminate [9]. In aerospace systems, laminated materials bound together to form complex shapes or to produce a material with high strength for its weight [10]. Laminates are thin sheets of materials bound together by an adhesive and, after the heat and/or pressure treatment (i.e., curing), formed into a structural material. In conventional applications, the response from the laminate is essential so that its strength and stiffness can be optimised [11]. The adhesive bond that exists between two adjacent layers is perfect such that it has almost zero thickness and no shear deformation. This is achieved through a forced fit. Thus, there is no adjacent slip of each lamina over another. The assumption of single-layer material indicates that displacements are continuous across the bond between two adjacent layers. The proper combination of composite material comes with the advantages of high stiffness-to-weight ratio, low weight, high strength, excellent corrosion and fatigue resistance [12]. The laminate structure also improves energy balance [13]. An assessment of the recent developments in the study of tapered laminated composite structures has been presented by He et al. [14].

A lot of works have been carried out to investigate the damage response of composite laminates [15–19]. Strait et al. [20] performed an impact test on composite laminate with various stacking sequence. It was observed that the stacking sequence has a significant influence on the impact resistance. To understand the response of composite laminate under impact force, finite element analysis was conducted by Wu and Fu-Kuo [21]. The strain and the stress distributions coupled with the displacements along the thickness of laminate were evaluated during the impact event. A damage predictive model in graphite/epoxy laminated composite under low-velocity point impact has been proposed by [22]. It was concluded that there exists a threshold impact velocity for laminated composites above which significant damage is produced and below which no delamination occurs. The damage resistance and residual strength for such laminates were studied by Dost et al. [23]. It was discovered that the laminate stacking significantly affects compression after impact results. Caprino et al. [24] investigated the effect of thickness of carbon/epoxy laminates using low-velocity impact. They were able to establish the onset of delamination. A model for predicting the residual strength of laminates with an indentation law has been presented by [25]. The residual strength as a function of the depth of indentation was well predicted, and good agreement was obtained when compared with the experimental data. However, the internal damage was not well predicted. Luo et al.[26] studied a methodology to assess the impact of damage initiation and propagation in a composite plate. By presenting both threshold strength and propagation strength for matrix cracking, it was shown that the main characteristics of impact damage could be projected. In the work of Hosseinzadeh et al. [27], the impact behaviour of four different fibre reinforced composite plates were studied by using standard drop weight under various energies. The threshold damage was predicted using Ansys-LS Dyna [28].

Drop and impact performance criteria for hand-held electronic gadgets like the cellular phones play a pivotal role in the design owing to the quantum of unexpected shocks they must withstand [29]. As such, the weak design points will be discovered during the impact behaviour analysis of cellular phone since actual testing is expensive and time-consuming [30,31]. Kim and Park [31] equally recognised that the design of product durability on impact greatly rely on the designer's experience and intuition. In their work, they employed LS-Dyna® [32] to perform a reliable drop simulation on a cellular phone and were able to predict potential damage locations in a cellular phone while comparing them with real statistical data. They, therefore, concluded that the development of a reliable system of drop/impact simulation would offer a robust and effective vehicle for the enhancement of the design quality; thereby reducing the product development cycle.

There is a drought of literature on the impact analysis of cellphones. However, a couple of works have been carried out on the subject matter by early researchers. The different issues involved in a drop test simulation of a cellular phone had been investigated by [33]. He used only the frame and the front to idealise the phone model while the material model is the hypoelastic model. From the mesh and time analyses, he concluded that the hexagonal element is most appropriate for analysis that is more than six. Hwan et al. [34] conducted drop tests on cellphones according to related test standards. They showed experimentally that the inner LCD modules of cellphones damage mostly when the cellphone falls with either of its front or back on top. Their experiments have indicated that horizontal impacts cause the most damage in cellphone drop tests. This type of fall often leads to the origination of cracks close to the midpoints of one edge of the module. A quick review of finite element analysis as a veritable tool to investigate the impact resilience of mobile phone has been compiled by Singh and Singh [31].

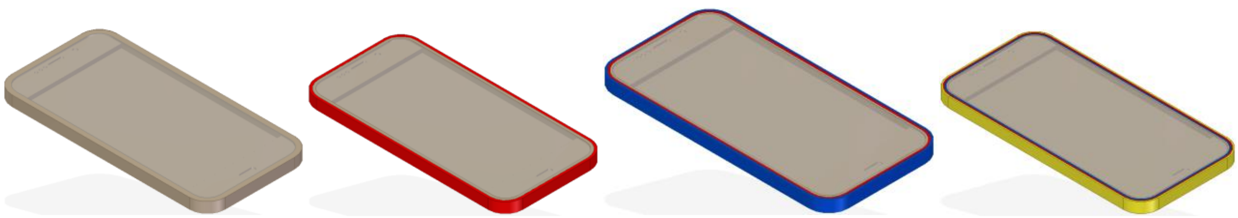

Fig. 2. Different number of casing laminates (a) single (b) two (c) Casing (d) four.

A survey of the literature shows that the reduction of impact response through the composition of the cellphone casing has not been explored. In this study, we explore a new laminate system as a way of reducing the effect of the impact load on the glass of a cellphone. Four case scenarios are painted. The case of a single layer (Fig. 2(a)), two-layer (Fig. 2(b)), three-layer (Fig. 2(c)), and four-layer (Fig. 2(d)) cellphone casing were investigated under five different drop heights. The influence of drop orientation to the mechanical loads on phone components is important in the drop test analysis of cellphone [31]. Grewolls and Ptchelintsev [35] suggested that sensitivity analysis is an appropriate and efficient tool to identify worst-case impact direction orientations. However, the present study looked at the back-face drop on the cellphone. The models in Figs. 2-5 has been done with Autodesk Inventor® [36] while the drop test analysis was performed in Solidworks® [37].

2. Drop test studies

The drop test module in SolidWorks® is used to evaluate the effect of the impact of the cellphone assembly with a rigid planar surface. The program automatically computes gravity and impact load and does not allow other restraints and loads. The test is height-controlled and depends on the following parameters: the drop height, h, the gravitational acceleration, g, and the impact plane orientation. Five different heights (ranging from 500mm to 2500mm at equal interval) were used for each of the four cellphone casing laminate configurations. The velocities, V at impact, is evaluated from Eq. (1),

$$V = \sqrt{2gh} \tag{1}$$

The cellphone motion is directed by gravity until it hits the rigid plane. The entire system results in a dynamic problem given by the equation,

$$P_i(t) + P_d(t) + P_e(t) = R(t) \tag{2}$$

where the inertia, damping and elastic forces are given as $P_i(t)$, $P_d(t)$ and $P_e(t)$ respectively, and are all function of time (t). Eq. (1) could be expressed in matrix and vector form as:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F\} \tag{3}$$

where $[M]$ is mass matrix, $\{\ddot{x}\}$ is acceleration vector, $[C]$ is damping matrix, $\{\dot{x}\}$ is velocity vector, $[K]$ is stiffness matrix, $\{x\}$ is displacement vector, and $\{F\}$ is an external force vector

Explicit time integration method is employed to solve the drop test problem. The critical time step is estimated based on the smallest element size; and to prevent divergence, the smaller value is used. As the solution progresses, the time step is internally adjusted. The solution time after impact is 100 microseconds. As the cellphone casing hits the floor, a stress wave emanates from the impact point and migrates through the entire body of the cellphone before it travels back.

3. Numerical experiment

The cellphone has two components: the phone casing made of polycarbonate ($C_{16}H_{14}O_3$) while the glass material is aluminium silicate (Al_2SiO_5). The material properties of these components are tabulated in Table 1. These material properties are implemented in Solidworks® for the drop test analysis.

Table 1
Material Properties of the Phone Casing and Screen.

	Material	Density, ρ (Kgm^{-3})	Modulus of Elasticity, E (GPa)	Poisson's Ratio, ν	Tensile Strength, σ (MPa)
Phone Casing	Polycarbonate ($C_{16}H_{14}O_3$)	1200	2	0.37	55
Phone Glass	Aluminum Silicate (Al_2SiO_5)	2630	81	0.24	

3.1. Elastoplastic material model

Most applications that involve kinematic hardening requires a full elastoplastic analysis. It is important to define the effective stress $\widehat{\sigma}$

$$\hat{\sigma} = \sqrt{\frac{3}{2} S_{ij} S_{ij}} \tag{4}$$

and the effective plastic strain, $\hat{\varepsilon}^p$

$$\hat{\varepsilon}^p = \int_0^t d\hat{\varepsilon}^p \tag{5}$$

functions respectively of the stresses and plastic strains in the body. The effective incremental plastic strain in Eq. (5) is given as

$$d\hat{\varepsilon}^p = \sqrt{2/3\, d\varepsilon_{ij}^p d\varepsilon_{ij}^p} \tag{6}$$

The condition for von Mises yield is given by Eq.(7)

$$\phi = J_2 - s_y^2/3 \tag{7}$$

where s_y is the yield strength of the elastoplastic material, and J_2 is the second stress invariant defined by deviatoric stress components as Eq. (8)

$$J_2 = \frac{1}{2} S_{ij} S_{ij} \tag{8}$$

The yield stress s_y could be defined as a function of the initial yield stress S_0, the plastic-hardening modulus, E_p and the effective plastic strain, $\hat{\varepsilon}^p$ given as Eq. (9)

$$S_y = S_0 + \beta E_p \hat{\varepsilon}^p \tag{9}$$

where β is a mixed hardening parameter that results to kinematic hardening when $\beta = 0$, and isotropic hardening when, while the plastic-hardening modulus, E_p is defined by the modulus of elasticity E and the input tangent modulus, E_t as Eq. (10)

$$E_p = \frac{E\,E_t}{E - E_t} \tag{10}$$

4. Simulation and results

The simulation is performed using a second-order tetrahedron element using Intel ® Core ™ i3-3220 CPU @ 3.30GHz. The simulation study, mesh and contact properties can be seen in Table 2.

Table 2
Study, mesh and contact properties for the simulation.

analysis type	drop test

large displacement	yes
drop height from centroid	500mm, 1000mm, 1500mm, 2000mm, 2500 mm
gravity	9.81 m/s^2
friction coefficient	0.47
target stiffness	rigid target
solution time after impact	100 microsec
mesh type	solid mesh
mesher used	standard mesh
element size	5.93498mm
tolerance	0.296749mm
total nodes	15198
total elements	18307
maximum aspect ratio	18.322
contact type	bonded

Figs. 3-6 show stress distributions for a cellphone with shock-absorbing ranging from one to four. They were all dropped from the same height 2.5m. As observed, the maximum concentration of stress is in the middle of the screen. However, the maximum stress concentration is recorded for the cellphone with four laminated casings.

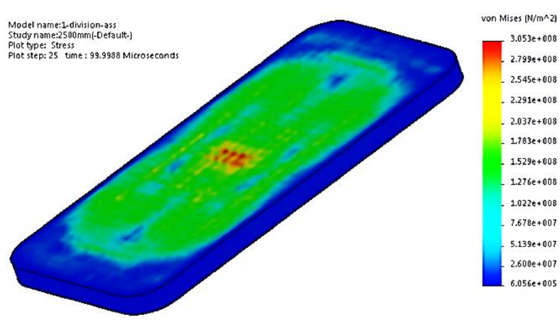

Fig. 3. Stress Distribution for a cellphone with Single Casing at 2500mm Drop Height.

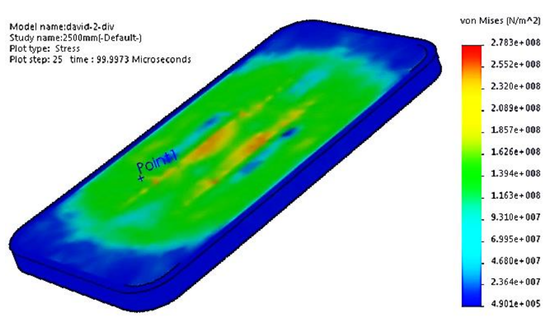

Fig. 4. Stress Distribution for a cellphone with Two Casing Laminate at 2500mm Drop Height.

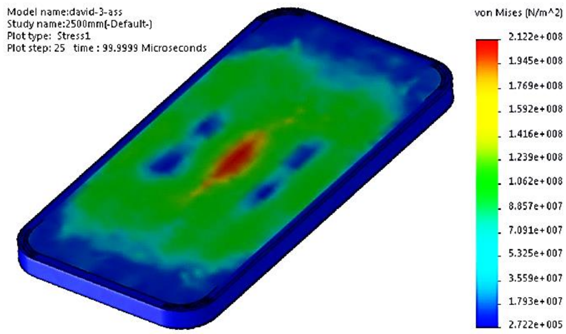

Fig. 5. Stress Distribution for a cellphone with Three Casing Laminate at 2500mm Drop Height.

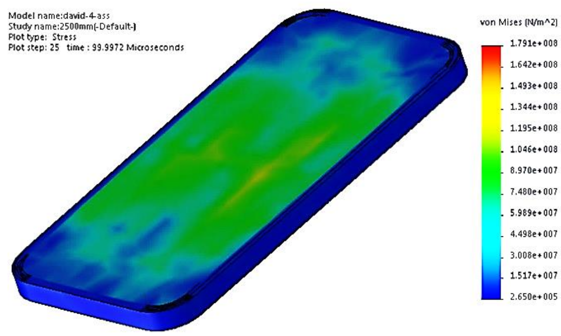

Fig. 6. Stress Distribution for a cellphone with Four Casing Laminate at 2500mm Drop Height.

In this paper, the effect of lamination of cellphone case on the impact resistance of smartphone screen is investigated. The strain energy, the maximum (or von Mises) stress and the displacement, each observed against the time of impacts, are illustrated for samples of single, two, three and four laminates. The results are as presented in Figs. 7 through 36.

4.1. Strain energy profile

Figs. 7-11 depicts the fluctuation of the strain energy of the cellphone laminates with time for various number of cellphone casing laminates at different drop distance. It is found that the profiles of strain energy against time for different drop distances are similar. However, the magnitude of the displacements, in these cases are different. Fig. 7 illustrates the material potentials against the time of impact with 500mm drop distance. The profiles for the single, two, three and four laminates are shown to be fluctuating along the time axis with improved overall strain energy as the number of laminates increases. Similar trends are presented for 1000mm (Fig. 8), 1500mm (Fig. 9), 2000mm (Fig.10) and 2500mm (Fig. 11) drop distances. It is noteworthy, however, that as the drop distances increase the maximum amplitudes of strain energy increases. The strain energy against time for various drop distances with a different number of phone casing laminates is shown in Figs. 12-15. The profile for the of the strain energy is the same for the various drop distances in each case of the number of laminates considered. In each of the graphs, the amplitude of the profile increases with an increase in the drop distance.

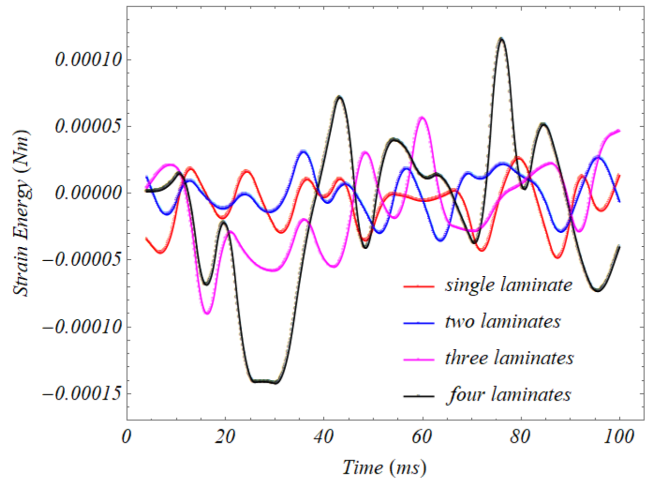

Fig. 7. Strain energy against time for various number of cellphone casing laminates at 500mm drop distance.

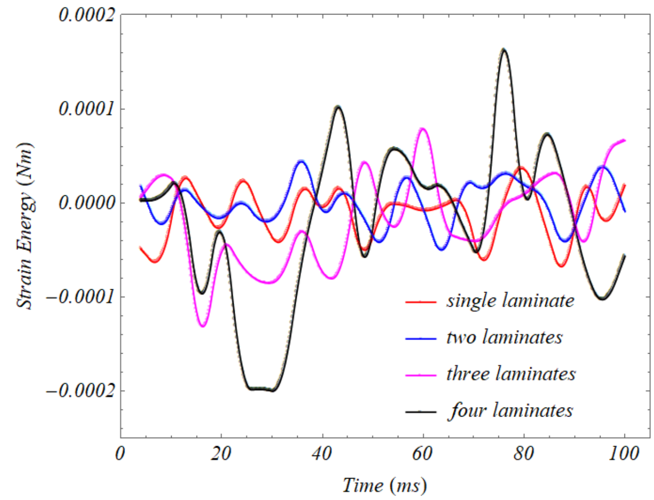

Fig. 8. Strain energy against time for various number of cellphone casing laminates at 1000mm drop distance.

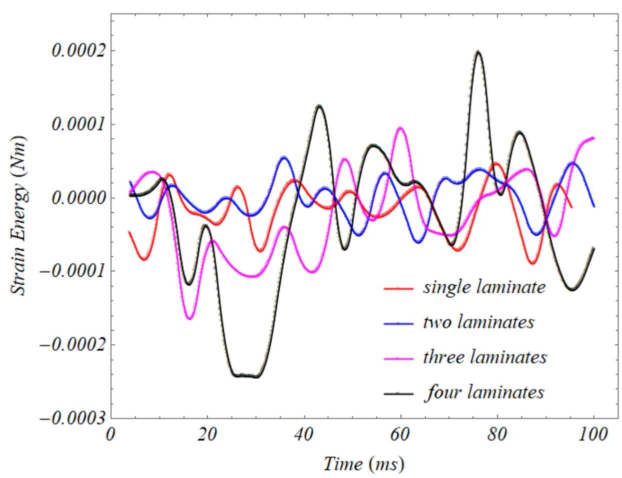

Fig. 9. Strain Energy against time for various number of cellphone casing laminates at 1500mm drop distance.

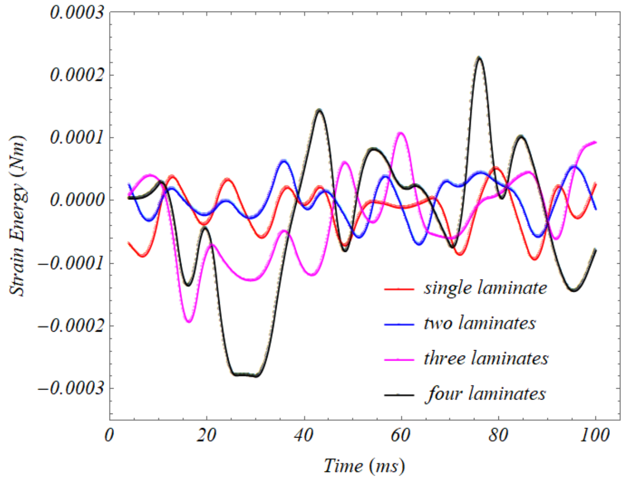

Fig. 10. Strain energy against time for various number of cellphone casing laminates at 2000 mm drop distance.

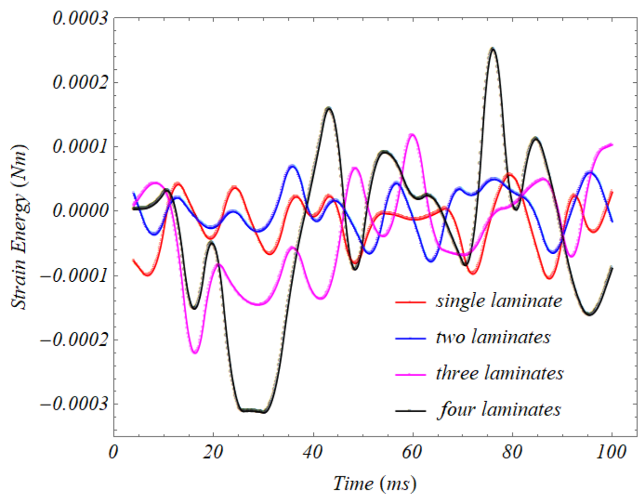

Fig. 11. Strain energy against time for various number of cellphone casing.

laminates at 2500mm drop distance

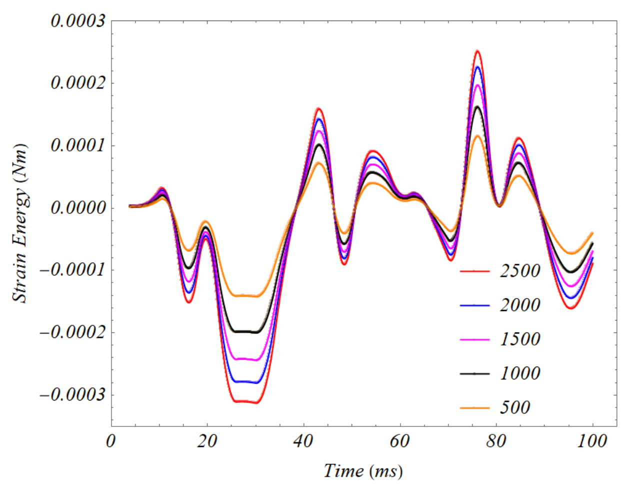

Fig. 12. Strain energy against time for various drop distances with four cellphone casing laminates.

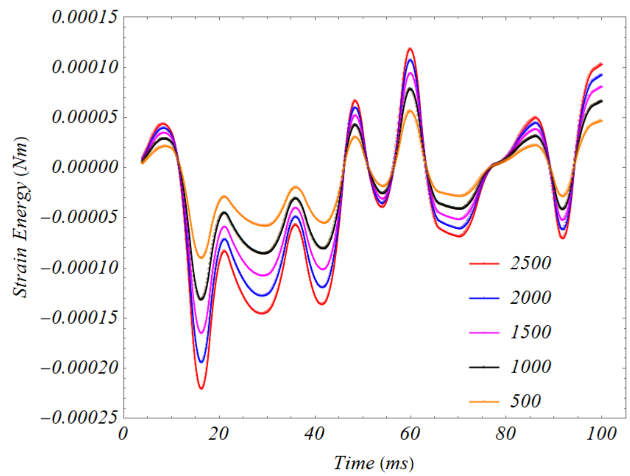

Fig. 13. Strain energy against time for various drop distances with three cellphone casing laminates.

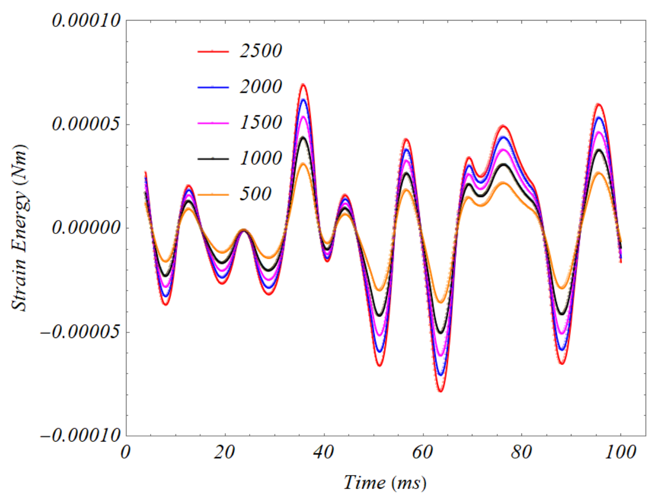

Fig. 14. Strain energy against time for various drop distances with two cellphone casing laminates.

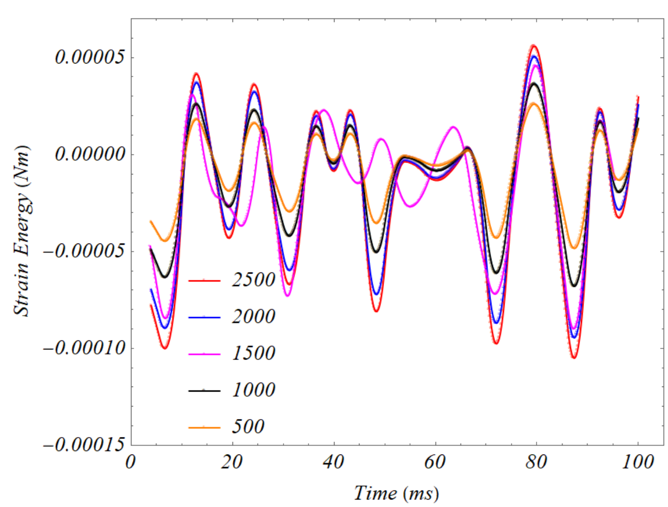

Fig. 15. Strain energy against time for various drop distances with a single phone casing.

4.2. Von mises stress profile

Figs. 16-20 illustrates the changes in of the von Mises stress of the cellphone laminates over time for various number of cellphone casing laminates at different drop distance. The graphs show that the contours of von Mises stress against time for different drop distances are similar, though there is a difference in the magnitude of their von Mises stresses. In Fig. 16, it is demonstrated that as the time of impact increases, the von Mises stress increases and fluctuates. The amplitude of fluctuation also increases as the number of laminates on the cellphone case increases. As the drop distance increases from 500mm to 1000mm (Fig. 17), the maximum stress increases significantly, as shown with increasing the time from about 5milliseconds to 20 milliseconds, also to 30 milliseconds and so on. The similarity in characteristics is demonstrated by Figs. 18 through 20. The von Mises stress against time for various drop distances with a different number of phone casing laminates is depicted in Figs. 21-24. The profile for the of the von Mises stress is the same for the various drop distances in each case of the number of laminates considered. In each of the graphs, the magnitude of the von Mises stress increases with an increase in the drop distance. The areas with maximum stress concentration correspond with the high stress level of the Aluminum Silicate (Al_2SiO_5) experimentally identified by Kim and Park [29].

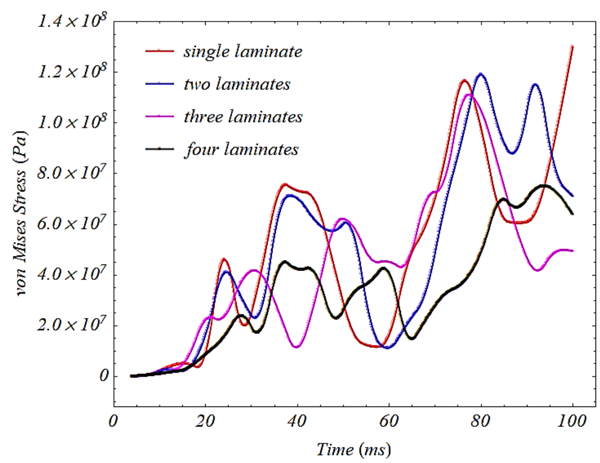

Fig. 16. von Mises stress against time for various number of cellphone casing laminates at 500 mm drop distance.

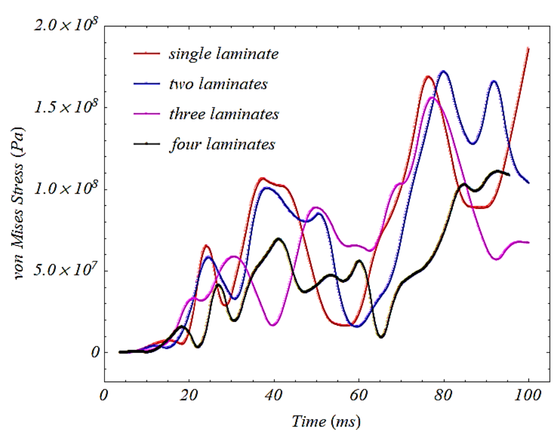

Fig. 17. von Mises stress against time for various number of cellphone casing laminates at 1000 mm drop distance.

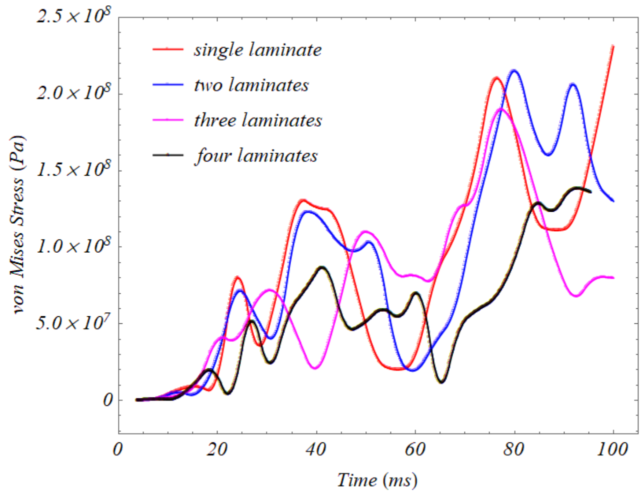

Fig. 18. von Mises stress against time for various number of cellphone casing laminates at 1500 mm drop distance.

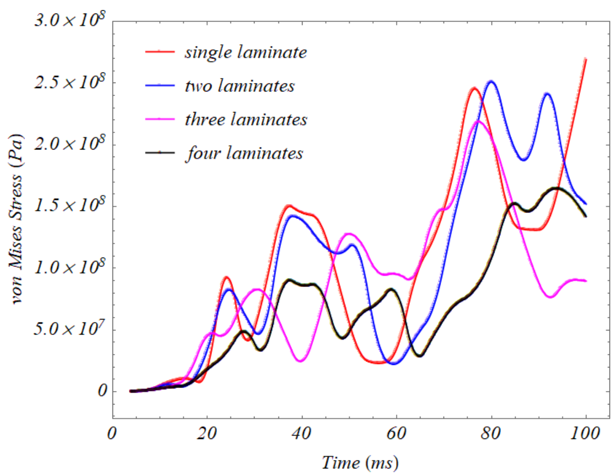

Fig. 19. von Mises stress against time for various number of cellphone casing laminates at 2000 mm drop distance.

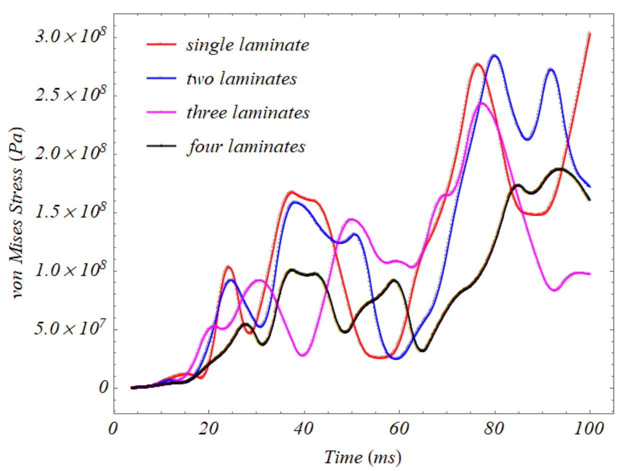

Fig. 20 von Mises stress against time for various number of cellphone casing laminates at 2500 mm drop distance.

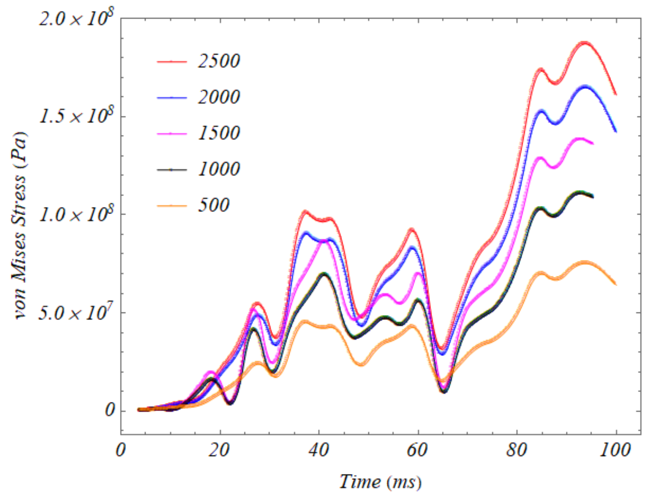

Fig. 21. von Mises stress against time for various drop distances with four cellphone casing laminates.

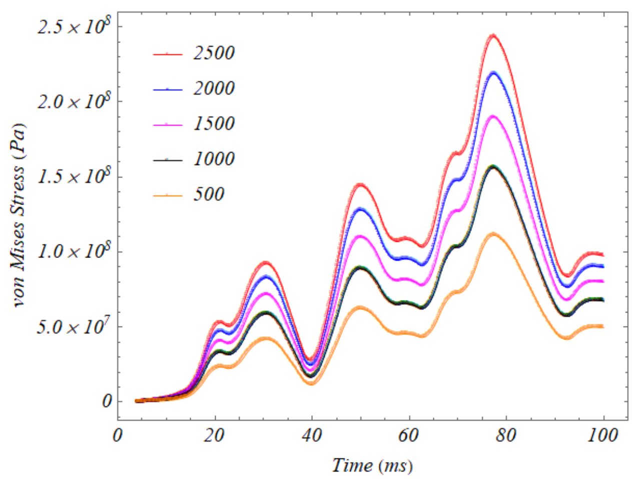

Fig.22. von Mises stress against time for various drop distances with three cellphone casing laminates.

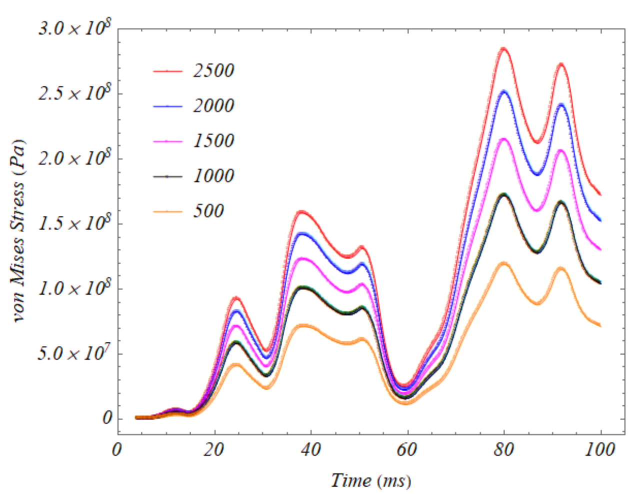

Fig. 23. von Mises stress against time for various drop distances with two cellphone casing laminates.

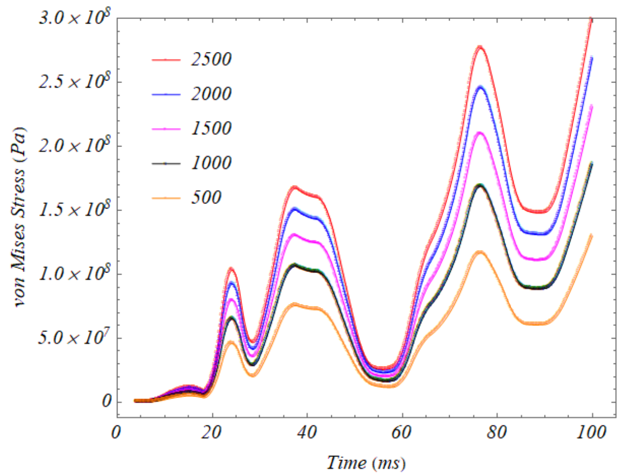

Fig. 24. von Mises stress against time for various drop distances with a single cellphone casing.

4.3. Displacement profile

Figs. 25-29 demonstrates the variations in of the displacement of the cellphone laminates with time for various number of cellphone casing laminates at different drop distance. The family of curves in Figs. 25-29 illustrates almost linearly increasing profiles as the displacement is plotted against time. The magnitude of the displacement also increases with increasing drop distances.

It is observed that between 0 to about 5 milliseconds, the potentials, the von Mises stresses and displacements, all show undefined results as the number of cycles at which the impact occurs will be so large and the endurance limits of the material would have been largely exceeded. The displacement against time for various drop distances with a different number of phone casing laminates is depicted in Figs. 30-33. The profile for the of the displacement is the same for the various drop distances in each case of the number of laminates considered. In each of the graphs, the magnitude of the displacement increases with an increase in the drop distance.

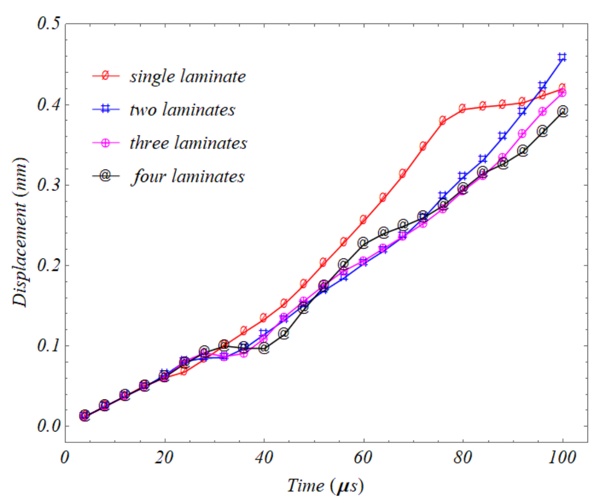

Fig. 25. Displacement against time for various number of cellphone casing laminates at 500mm drop distance.

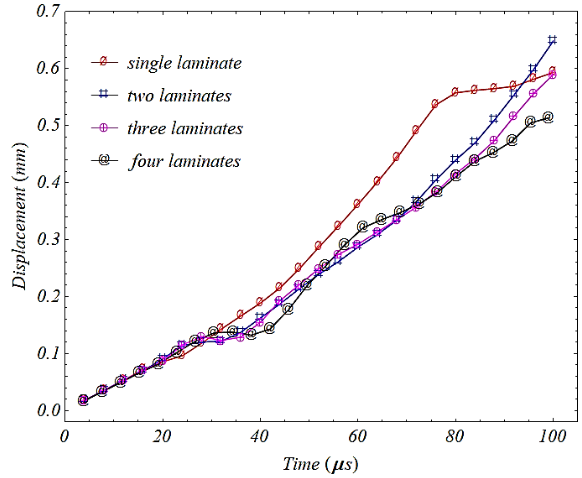

Fig. 26. Displacement against time for various number of cellphone casing laminates at 1000mm drop distance.

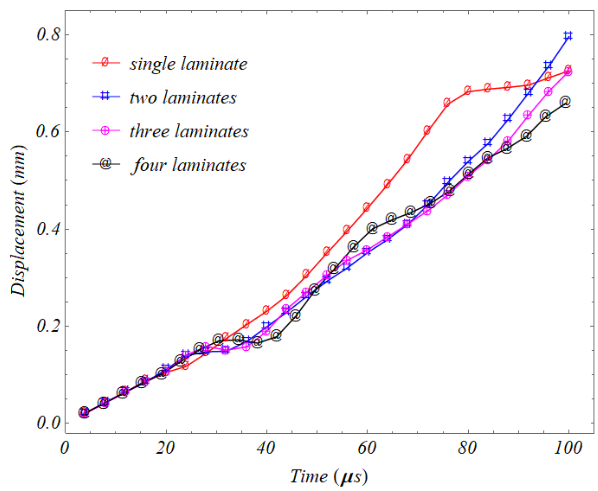

Fig. 27. Displacement against time for various number of cellphone casing laminates at 1500mm drop distance.

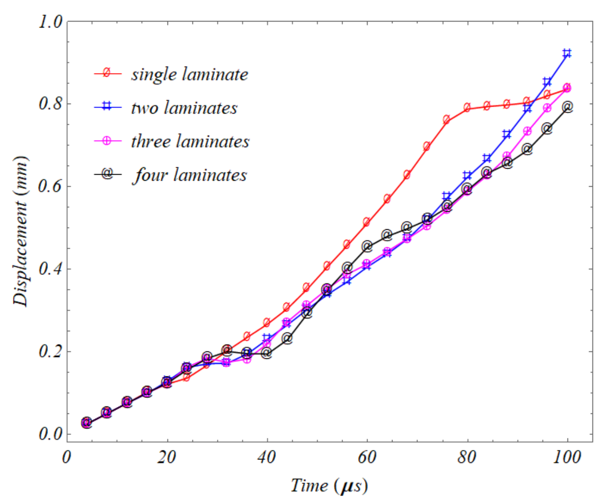

Fig. 28. Displacement against time for various number of cellphone casing laminates at 2000mm drop distance.

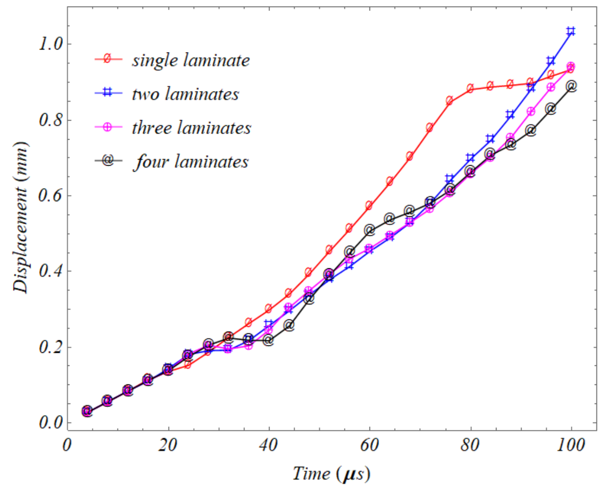

Fig. 29. Displacement against time for various number of cellphone casing laminates at 2500mm drop distance.

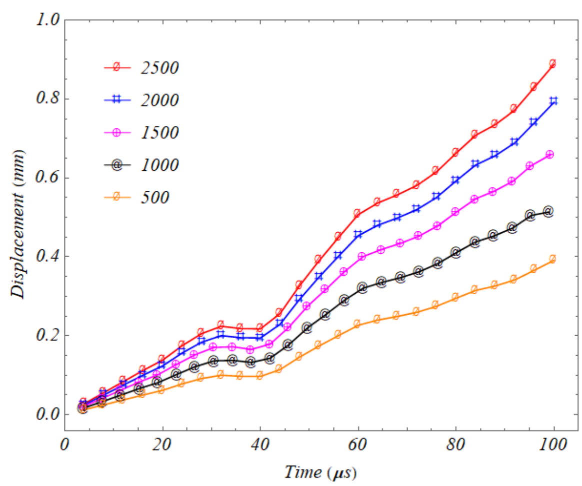

Fig. 30. Displacement against time for various drop distances with four cell phone casing laminates.

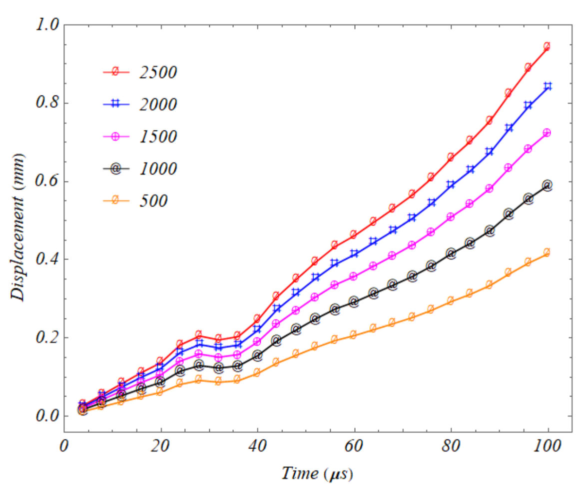

Fig. 31. Displacement against time for various drop distances with three cell phone casing laminates.

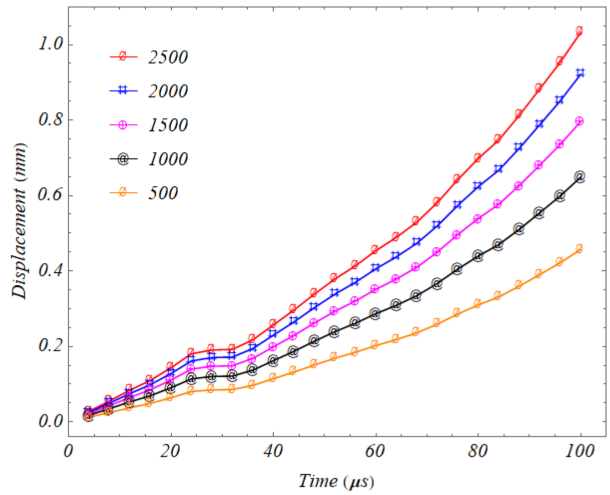

Fig. 32. Displacement against time for various drop distances with two cell phone casing laminates.

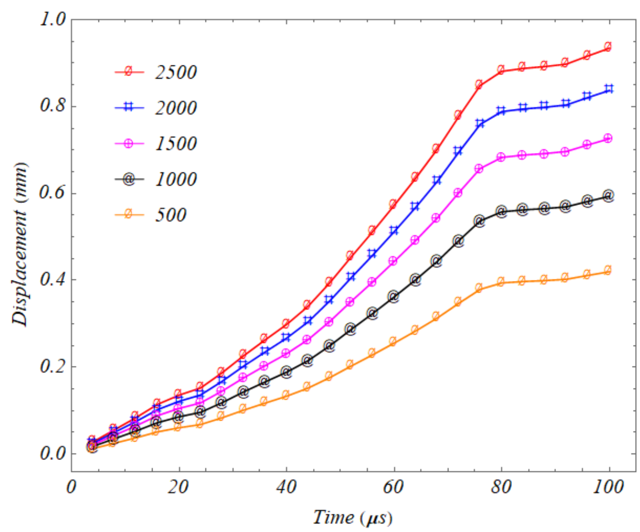

Fig. 33. Displacement against time for various drop distances with a single cell phone casing.

Conclusion

In this paper, the numerical investigation of the effect of laminated cellphone case on the impact resistance of smartphone screens has been carried out. It is observed that between 0 to about 5 milliseconds, the potentials, the von Mises stresses and displacements, all show undefined results as the number of cycles at which the impact occurs will be so large, and the endurance limits of the material would have been largely exceeded. Results from the stress, strain energy, and displacement responses reveal a drop in their maximum values as the number of laminate layers increases, depicting an inverse relation between the formers and the later. The reformation of cellphone cases as laminates will help the phone users to save some cost as a result of frequent change or repair of screens.

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