Journal of Engineering Science and Technology
Vol. 2, No. 2 (2007) 200 - 210
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A COMPARISON OF ENERGY ABSORBING CAPABILITIES OF PAPER AND STEEL STRUCTURES SUBJECTED TO PROGRESSIVE FAILURE UNDER FREE FALLING OBJECTS

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Abstract

An inverted paper cup of 0.26 mm thickness was subjected to deformation under a freely falling steel ball at a velocity of 2.77 m/sec. The deformed features of the paper cup were measured. The dynamic loading event was simulated using piecewise linear plasticity material model in LSDYNA. Deformed shape of the paper cup in finite element model matched closely with experimental results with ignorable small discrepancies. The paper cup was able to absorb all the kinetic energy of the falling steel ball for the above mentioned falling speed and the ball did not bounce out of the cavity generated by the impact. In LSDYNA a similar size steel cup was also subjected to a freely falling ball with same speed and the energy absorbed was compared to the energy absorbed by the paper cup. It was found that under similar conditions a paper cup would undergo a significant progressive failure and absorb all the energy of the falling object.

Keywords: Progressive Failure, Paper Cups, Piecewise Linear Plasticity, LSDYNA, Energy Absorbed.

1. Introduction

Depending upon the situation where the safety of a falling object or the target material or both may be sought for, the damage caused to the materials (impactor & target) is dependent on many variables like shape, size, velocity, and the angle

Nomenclatures

KE	Kinetic Energy
m	Mass (kg)
r	Radius of the steel ball (m)
v	Velocity ($m.s^{-1}$)
Greek Symbols	
ρ	Density of the sphere ($kg.m^{-3}$)

of impact. The focus of the present research is on the low velocity falling objects where the above mentioned objectives would be explored. The applications of the present research may be helpful but not limited to understand the effect of a falling rock on the body of an automobile, the emergency landing of a helicopter on a hard surface or the damage caused to a delicate product by simply falling on a factory floor. In cases where the damage is unavoidable it would be sought in many cases that the failure of the part should follow a continuous progressive order. This would be of great significance when the safety of occupants in a car crash is the objective. Another objective is to explore the materials which may follow progressive failure on impact.

2. Experimental Procedures

The paper cups chosen to carry out the failure experiments are shown in Fig.1. The dimensions of the paper cup subjected to falling loads are shown in Fig. 2. The thickness of the paper cup body was 0.26 mm. The base and bottom ring were 0.29 and 0.69 mm thick. The paper cup seam had a thickness of about 0.50 mm.

Fig. 1. Paper Cups used in the experimental work.

To establish the material properties, tensile tests on the paper specimens cut out of the cup were carried out. Polymer testing machine was used to carry out testing. A few tensile specimens are shown in Fig.3.

Tests were performed at 5, 10 and 20 mm/min loading rates. A typical engineering stress-strain curve derived from the tensile tests at 20 mm/min is shown in Fig.4. From this data the true stress-strain values were calculated to be used in finite element simulations that are shown in Fig.5. The density (844 kg/m^3) of the paper material under consideration was measured and the Poisson's ratio (0.182) was also determined experimentally using two strain gages pasted at 90^o on the tensile specimens. Depending on the water content the material properties of paper may vary significantly [1]. There has been a lot of discussion about establishing the elastic modulus of paper in the literature [2], but in the present studies as the focus was upon rather thicker section of paper used to manufacture paper cups the unnecessary complications and details regarding this material have been avoided. The material properties were established in the controlled room temperature and humidity conditions.

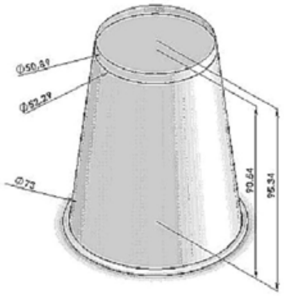

Fig. 2. Paper Cup Base, Base Ring, Body, and Cup Seam had 0.29, 0.69, 0.26, and 0.50 mm Thicknesses Respectively.

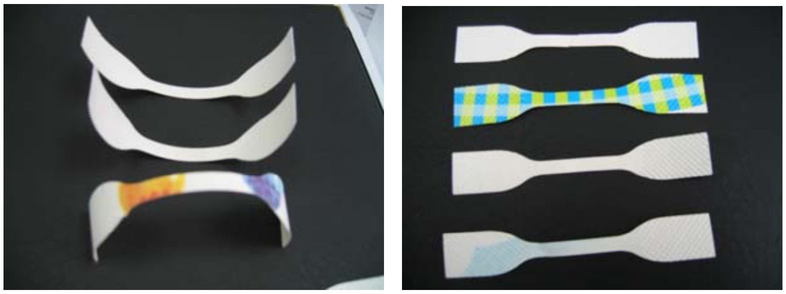

Fig.3. Specimens Obtained from the Paper Cups Before and After Testing.

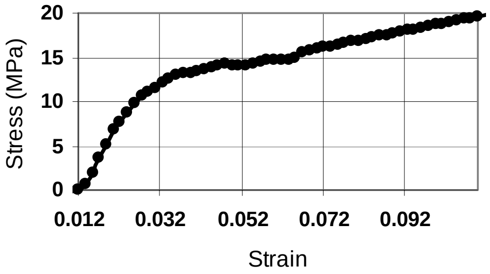

Fig.4. Engineering Stress-Strain Curve for Paper Specimens.

2.1 Drop tests

The drop tests were conducted by releasing a steel ball of 38 mm diameter from a height of 0.76 meters on the top of inverted paper cup. The damage caused to the paper cups is shown in Fig.6. As it can be seen that the kinetic energy of the ball is fully absorbed by the paper cups and the solid steel ball comes to rest in the cavity generated due to the impact. In present research the velocity of a freely falling steel ball before hitting the ground was observed to be of the order of 2.77 m/sec when released from a height of 0.76 meters. A data recorder was set at 1000 Hz and strain signals were recorded when the ball hit flexible strain gage posts arranged vertically at a distance of 100 mm apart. The measured speed was recorded as 2.77 mm/m sec which give a value of 2.77 m/sec.

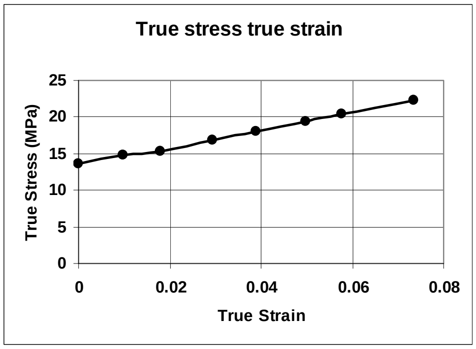

Fig.5. True Stress-Strain Curve for Paper Material.

Fig.6. A Typical Shaped Cavity Generated in the Paper Cup Due to the Ball Impact.

3. Finite Element Analysis

The paper cup model was generated in ANSYS/LSDYNA version 9.0. The above shown cup was discretised into 4-node thin shell elements with Belytschko-Tsay formulation. 10-node solid tetrahedron elements were used to mesh the steel ball. The material model for the steel ball was considered to be rigid and un-deformable.

Piecewise linear plasticity (*MAT_PIECEWISE_LINEAR_PLASTICITY) material model was used for the paper cup. For the steel cup the plastic kinematic (*MAT_PLASTIC_KINEMATIC) material model was used.

Fig.7 shows the initial model of an un-deformable rigid ball and the inverted paper cup and the deformed cup after impact. The colors show the difference in the thickness of various parts of the model. The picture on the right shows the deformed model after 60 milli seconds (m sec). In all simulations as in experimental work the steel ball was dropped on to the cup structure at a location offset 5 mm from the centre of the cup.

Fig.8 shows the detailed deformation mode after 52.8 m sec while Fig.9 shows the very small deformation for steel cup at 16.8 m sec. As the steel ball bounced back from the steel cup surface after 5 m sec, the stress and strain data after this moment will not undergo any significant variation. In this particular case the deformation seems to be severer than the experimental results. The reason may be that tensile test material properties do not account towards the compression stresses generated in the FE model as it is well known that most of the materials have higher failure stress under compression. The constraints imposed were on the nodes located at the bottom circular edge of the cup in the Y and Z directions to represent the contact between the cup and the hard floor below but as a matter of fact it is very complicated to implement the real boundary conditions as in dynamic loading of the cup, the bottom edge momentarily might experience stick and slip boundary conditions which might require a high speed camera to capture the event and then decide about the actual constraints on the FE model.

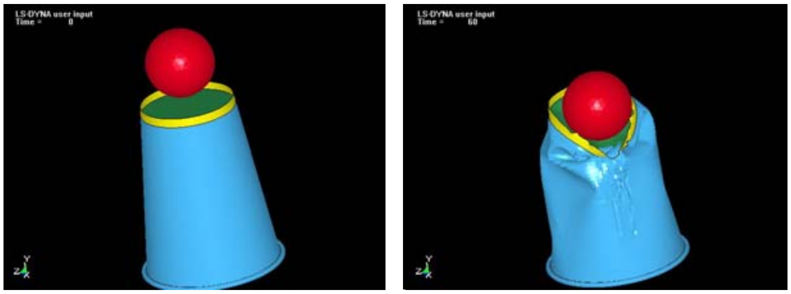

Fig.7. Initial Un-deformed and the Final Deformed Model of the Paper Cup at 60 m sec.

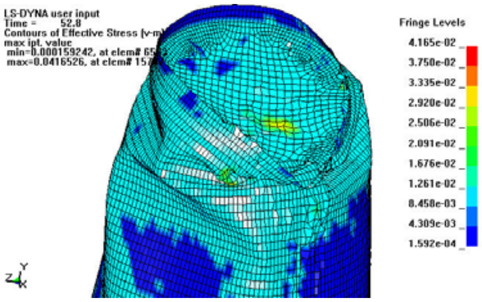

Fig.8. Effective Von Mises Stresses in Deformed Paper Cup at 52.8 m sec.

4. Absorbed Energy

For the freely falling ball the kinetic energy is calculated using Eq. (1).

$$K.E = \frac{1}{2} m v^2 \tag{1}$$

The velocity of the freely falling steel ball was measured to be 2.77 m/sec at the time of contact with the target material. Mass of the steel ball was calculated using equation (2).

$$m = \frac{4}{3} \pi r^3 \times \rho \tag{2}$$

For the steel ball used in the experiments the ball radius was 19 mm and for a density of the steel ball (ρ=7800kg/m^3) the calculated mass was 0.224 kg. For the above mentioned velocity the kinetic energy was calculated to be 0.859 J.

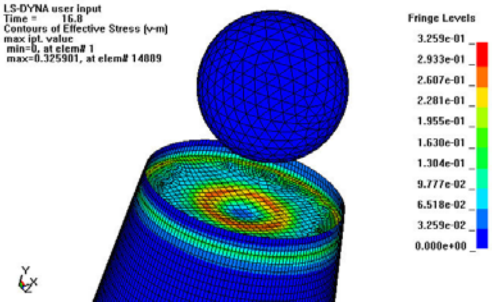

Fig.9. Effective Von Mises Stresses in Deformed Steel Cup at 16.8 m sec.

As the steel ball was dropped on the paper cup the kinetic energy of freely falling ball was fully absorbed by the paper cup material and the ball came to rest within 20 m sec. This is shown by the kinetic energy variation in Fig.10. After impacting the steel cup the steel ball bounces back within 5 m sec which can be seen in Fig. 9. The energy retained by the steel ball can be visualized in Fig. 11.

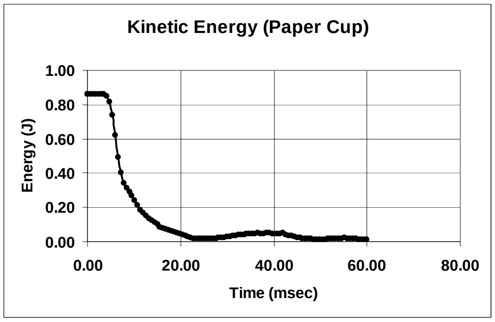

Fig. 10. The Kinetic Energy of Steel Ball is Fully Absorbed by the Paper Cup.

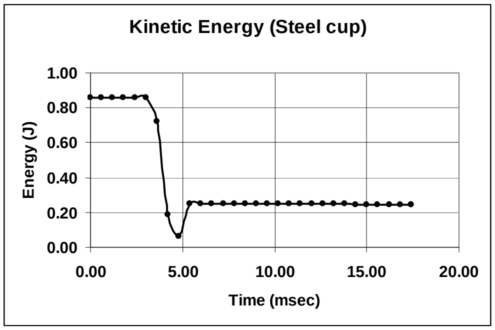

Fig.11. Steel Ball Retains Some of its KE and Bounces from the Steel Cup Surface.

5. Plastic Strain Variation

The total strain accumulation within 60 m sec in paper cup occurs in a gradual manner as the steel ball settles down into the newly generated paper cup cavity. This is shown in Fig. 12. But in case of steel cup the steel ball bounces back from the surface within 5 m sec which leaves very small amount of plastic strain into the steel cup body. Further straining would not be possible as the ball is no more in contact with the target surface. The bouncing back of ball can be inferred from Fig.10 and Fig.12 The plastic strain variation as shown in Fig.12 and Fig. 13 was obtained from a randomly selected element at the base of the paper and steel cup.

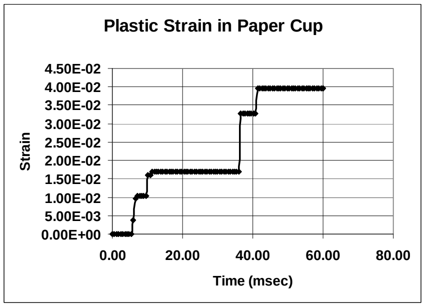

Fig.12. Plastic Strain has Accumulated in Gradual Steps in Paper Cup.

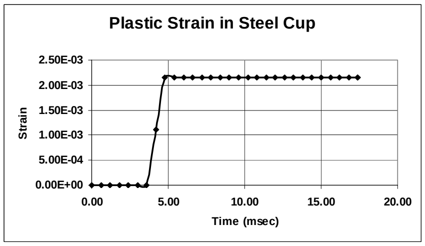

Fig. 13. Plastic Strain Reached its Maximum Value in a Single Step in Steel Cup.

5.1 Internal energy

The paper cup was modeled as three parts consisting of body of the cup, the cup flat base, and the base ring as shown in Fig.7. The internal energy of the three parts at the collision event is shown by three curves in Fig.14. The circular flat base is the part that is subjected to direct impact prior to other parts. The internal energy in this portion of the cup therefore increases in steps due to high vibrations. As a result of subsequent deformation of the flat base the body of the cup is the second part that undergoes deformation. The internal energy of the body of the paper cup undergoes a gradual increase of internal energy and after 25 milliseconds it stabilizes. The base ring is the last part of cup that undergoes deformation and the internal energy of the ring structure is represented by hollow circular points. As the mass of circular ring is the smallest, the energy absorbed is also analogous.

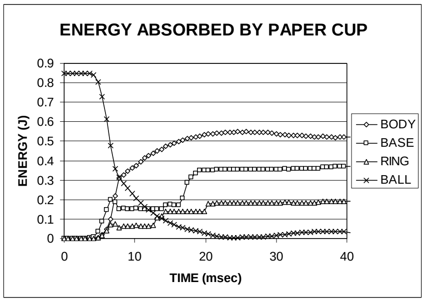

Fig.14. The Energy Absorbed by Three Parts of Paper Cup.

The internal energy of steel cup on impact is shown in Fig.15.~16. In Fig.15, the comparison between the energy absorbed by the steel cup body and the base ring is shown. The energy absorbed by the cup body is larger compared to the ring owing to the fact that the mass of body is larger. In Fig.15, the internal energy of circular flat base is shown which being the maximum energy because the flat base was the only part to undergo maximum plastic strain. The internal energy in the flat circular base rises to a maximum value of 0.7J and then stabilizes at 0.6J. Fig.17. shows the energy absorbed by three parts of steel cup and the energy drop in the steel ball hitting the steel cup. As the steel ball comes into contact with the base of the cup and remains in contact for a very short period of 2~3 m sec the energy absorbed by the cup base increases to a maximum and then settles down to a constant value. At this moment the steel ball retains about 0.25 J of energy as it slightly bounces off the surface of cup base unlike in case when the steel ball comes into contact with paper cup base where it loses all its kinetic energy at 25 m sec from the start of contact process. It is to be noted that the energy absorption in paper cup is delayed while in case of steel cup it happens within first 5 m sec.

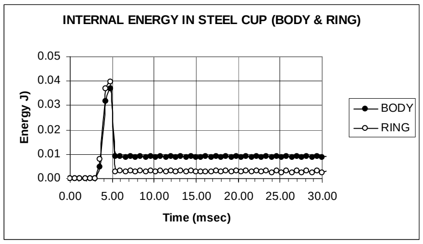

Fig.15. Internal energy of steel cup (cup body and base ring).

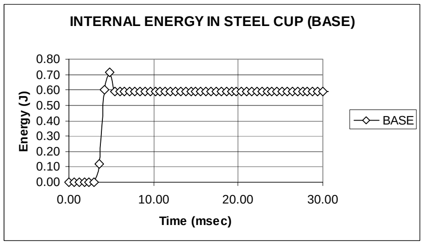

Fig.16. Internal energy of the cup base. Maximum energy was absorbed by the base.

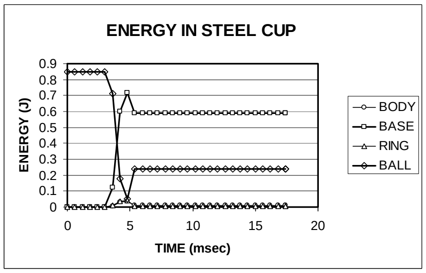

Fig.17. Energy absorbed by steel cup

6. Discussion

For low strain rate impact events like vehicle crash, instruments falling on delicate parts in a factory, or free falling of objects prone to damage, it is desirable in many such instances that the failure process should follow a continuous order with delayed time to absorb energy. Progressive failure during a car crash would enhance the chances of occupant survival and provide protection from lethal injuries. In an emergency landing of a light weight helicopter the stiff pads meant for landing may not be able to protect the structure. It is therefore necessary to explore materials that would provide enough structural strength along with progressive, slow and stable failure. Composite materials may provide a good solution to this problem but they may not be suitable in all situations because of their comparatively higher stiffness or brittle failure behavior. Moreover the geometry of energy absorbing components of a vehicle structure becomes an important factor to ensure that during crash events the progressive failure could be achieved. Instead of regular shaped composite tubes the cup shaped components should be investigated in more detail.

In the present study it has been found that though the paper cups lack the structural strength compared to steel cups but they still are able to absorb all the kinetic energy of a free falling steel ball and ensure a progressive failure[3~8] for limited range of kinetic energy. Comparison of plastic strain history in Fig.12 and Fig.13 shows that the deformation in a stiffer material follows a sudden rise while low strength material follows a progressive accumulation of strain over the time. Falling height for the steel ball was adjusted such that it would provide only the required amount of deformation. In a very similar fashion the structures could be designed for low speed falling events where only desirable amount of deformation could be achieved. In present case paper cups have been found to be best candidate material with suitable geometric shape that can ensure progressive failure and absorb nearly all kinetic energy during impact for limited falling velocity of a steel ball.

7. Conclusions

Inverted paper cups were subjected to freely falling steel ball of 0.22 kg mass. The falling height was adjusted such that only required amount of damage was achieved. The impact loading event was simulated using LSDYNA and a very good correlation between the experiment and the finite element model was obtained. Simulation was repeated on a steel cup and the kinetic energy absorption capabilities of the two cups were compared. Failure process was closely studied and following conclusions were made.

1. Under controlled conditions of velocities and geometrical shapes the paper cups were able to absorb all the kinetic energy of a freely falling steel ball for limited amount of deformation in the paper cups.
2. Simulation work showed a very close agreement with the experimental evidence and results were validated for the extent of deformation.
3. Simulations were repeated with steel cups as the target material where it was found that though the steel cups were far stronger than the paper cups but their capability of energy absorption[9,10] was lower than the paper cups because after the impact, the steel ball retained some of its kinetic energy and bounced back.
4. Following the experimental procedure and its validation by finite element analysis the structural components can be designed that would provide required amount of progressive failure and absorb the kinetic energy of falling objects effectively.
5. Comparison of energy absorption capability of steel and paper cups showed that in case of paper cups a delayed time to absorb all the kinetic energy was achieved which was five times better than in case of steel cup.

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