

## ***Impact Resistance of Polypropylene: A Numerical Study***

***Mashuka Jahan<sup>1</sup>, Md. Shariful Islam<sup>2</sup>***

*Assistant Professor<sup>1</sup>*

*Department of Mechanical Engineering*

*Khulna University of Engineering & Technology, Khulna-9203, BANGLADESH*

*Corresponding Author's Email id: msislam64@gmail.com<sup>1</sup>*

### ***Abstract***

*Polymer products including polycarbonate (PC), polymethyl methacrylate (PMMA), and polypropylene (PP) have a variety of uses in armour, like body and face shields, helmets, armoured vehicle windows, and car bumpers. The most difficult aspect of these applications is ensuring the safety of the users. Since these materials are often subjected to impact loading, it is critical to investigate their failure under such conditions. An analytical model is built in this paper to predict the maximum impact force for low velocity impacts, and numerical simulation is used to predict the same for polypropylene materials. The low velocity impact behavior of polypropylene is investigated up to the elastic limit by using commercially available software ABAQUS 6.13. The type of the simulation was explicit. The maximum force for 20J energy was 18.01 kN and the results are close to the theoretical values.*

***Keywords:*** *Polycarbonate (PC), Polymethyl methacrylate (PMMA), Polypropylene (PP)*

### **INTRODUCTION**

When two or more bodies (at least one is moving) collides each other, then the bodies apply a very high force on each other for a very short period of time. This phenomenon is known as impact. This

impact force has a greater effect on how the bodies will response rather than a comparatively lower force applied on the body for a longer period of time. This is due primarily to the stress increases that happen when transient stress waves

overlap. When the loads are slowly applied these effects are minimal. In everyday life nothing is stationary, things are moving all the time. During moving some unexpected incident may happen such as accidents and even if it is a low velocity impact it can create internal damage that may not be visible but greatly affect the strength and performance of the material in long time.

If the impact velocity is within 1-10 m/s then the impact is often referred low velocity impact. Richardson et al. [1] defines low velocity impact according to Sjoblom et al. and Shivakumar et al., [2, 3] where the upper limit of the velocity is up to 1 to 10 m/s. Cantwell et al.[4] also classified low velocity impact up to 10 m/s but Arbate [5] stated that if the velocity is less than 100 m/s then it can be considered as low velocity impact. It should be noted that these ranges are somewhat arbitrary. Some example of low velocity can be, walking (1m/s), running (4m/s), and speed of a car at freeway (30 m /s). Low velocity impact test can be carried out in drop weight impact machine where the striker is kept above the specimen to a certain height and then release it from there to allow it to fall freely due to gravity. The height from where the striker placed should be such that the striker gains the required velocity

just before the impact. In this case the potential energy of the striker completely converts to the kinetic energy.

Bumpers are used in cars for absorbing shock or impact at low velocity like accidentally hitting while reversing the car. These are integrated with the front or rear ends of a motor vehicle. The elements minimize height mismatches between vehicles and protect pedestrians from injury. It is the focus of this paper to study the impact force of Polypropylene to use it as a material in making bumper. Different materials have different behavior in impact compared with static loading conditions. This paper is organized in the following sections: section 2 describes the analytical model developed, section 3 includes the detail of the numerical simulation, section 4 includes the results with discussion and finally, section 5 is conclusion.

## THEORETICAL MODEL

As shown in Fig. 1, the indentation load  $P$  of a spherical indenter is a function of the indentation depth  $h$  and indenter radius  $R$  based on Hertz's contact law[6, 7],

$$P = \frac{4}{3} \sqrt{RE_r} h^{\frac{3}{2}} = C_{ID} h^{\frac{3}{2}} \quad (1)$$

Where  $C_{ID}$  is the contact stiffness for a nano-indentation process; and the reduced

modulus  $E_r$  is determined by Young's modulus  $E$  and Poisson's ratio  $\nu$  for the isotropic and homogeneous target materials, as in

$$\frac{1}{E_r} = \frac{1-\nu_i^2}{E_i} + \frac{1-\nu}{E} \quad (2)$$

Where the subscript I refers to the indenter

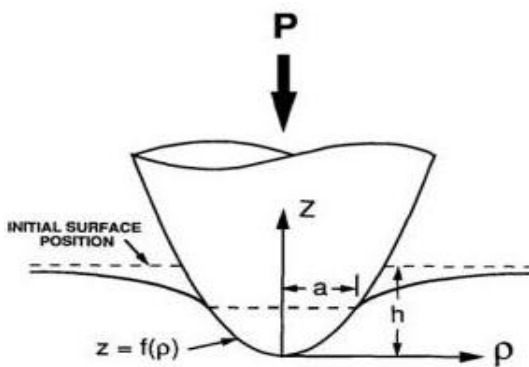


Fig. 1: Typical indentation process.

During a dynamic indentation process, the total force acting on the indenter is indentation force from the target only. Thus,

$$\sum F = P = ma \Rightarrow m\ddot{h} + Ch^{\frac{3}{2}} = 0 \quad (3)$$

The maximum impact force is achieved at the zero speed of the indenter and it is simply determined using the impact energy of the indenter/projectile, and the contact stiffness between the indenter and target  $C_{IP}$  is, as in [7]

$$P_{max} = C_{IP}h^{\frac{3}{2}} = 1.14\sqrt[5]{E^3C_{IP}^2} \quad (4)$$

In case of nano indentation the contact stiffness of impact has the same form and based on Hertz's contact law with different length-scales, and with indenter radius  $R_{IP}$ , [7]

$$C_{IP} = \frac{4}{3}\sqrt{R_{IP}E_r^{IP}} \quad (5)$$

Based on the relationships provided above, the contact stiffness of impact ( $C_{IP}$ ) can be obtained from the nano-indentation test for the same target material system (i.e.,  $C_{ID}$ ) based on a scaled relation,

$$C_{IP} = C_{ID}\sqrt{\frac{R_{IP}}{R_{ID}}}\left(\frac{E_r^{IP}}{E_r^{ID}}\right) \quad (6)$$

For composites, steel projectile impact, and a diamond nano-indenter, we have  $E_r^{IP}/E_r^{ID} \gg 0.9$ . Given the above observation (i.e., Eq. 6), we propose to construct an efficient procedure that circumvents impact testing with which damage initiation and maximum damage can be easily determined.

A very useful approach to study impact dynamics is to consider the balance of energy of the system. The deformation of

the structure is resulted from the kinetic energy of the projectile [7]. The kinetic energy of the projectile is used to deform the structure and thus the maximum deformation of the structure occurs when the kinetic energy of the projectile becomes zero.

The deformation of the structure may include bending, shear deformation and if the deformation is large then it may include membrane stiffening effect. If the impact energy is such that it creates very small amount of damage to the structure then the energy required to create damage can be neglected. So the energy balance equation can be written as[7]

$$\frac{1}{2}MV^2 = E_b + E_s + E_m + E_c \quad (7)$$

Where  $E_b$ ,  $E_s$  and  $E_m$  refer to the energy in bending, shear and membrane deformations respectively.  $E_c$  is the energy stored in the contact region during indentation.

The Hertz contact law can be expressed

$$P_{\max} = C_{IP}h^{\frac{3}{2}} \quad (7)$$

If the impact structure is thick and deformation of the structure is negligible,

then it can be considered that all the kinetic energy is used to indent the structure.

The maximum contact force becomes,

$$P_{\max} = 1.14(E^3C_{IP}^2)^{0.2} \quad (8)$$

Where E is the kinetic energy of the projectile

## NUMERICAL SIMULATION

A dynamic explicit finite element simulation was carried out in available commercial software Abaqus 6.13 to help in the understanding of the basic mechanics of the problem. The model is discussed in the following section.

### *Modeling of Target Plate*

The problem can be treated as a 3 dimensional axi symmetric problem where the stress varies along the radial direction from the center. The target plate was a 3D deformable object (Polypropylene) with a material property as mentioned in table 1.

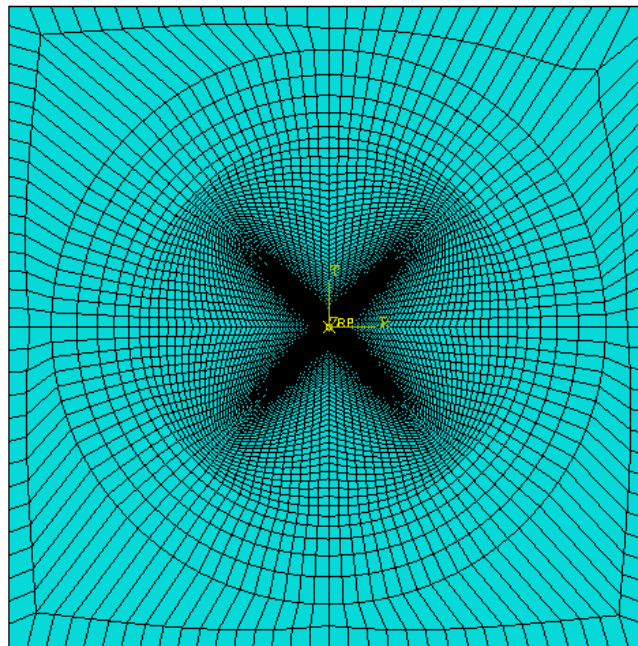
C3D8R elements were used to mesh the target plate which is 3D 8 node brick element with reduced integration and hourglass control. Figure 2 shows the top view of the mesh on target plate.

A very fine mesh were used in the center (at the impact area) to capture various parameters accurately and gradually

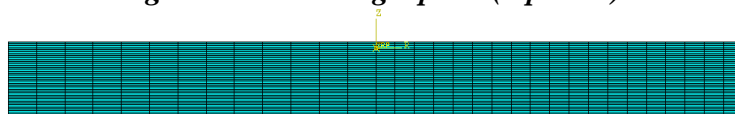
decreased resolution of mesh were used outside of the impacted area. Figure 3 shows the mesh from side view.

**Table 1: Typical properties of polypropylene [8, 9]**

Property	Polypropylene
Density(kg/m <sup>3</sup> )	905
ElasticModulus(GPa)	1.3
Poisson's Ratio	0.42
Tensile strength(MPa)	31-41
Compressive Strength at Break(MPa)	38-55
Flexural Strength at Break(MPa)	41-55

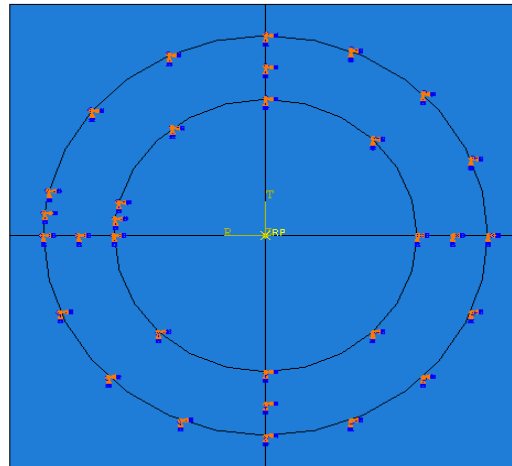


**Fig. 2: Mesh on target plate (top view).**



**Fig. 3: Mesh on target plate (side view).**

Fixed boundary condition is used in the top and bottom clamped area for the target plate. Figure 4 shows the bottom boundary conditions. The top boundary condition is also same.



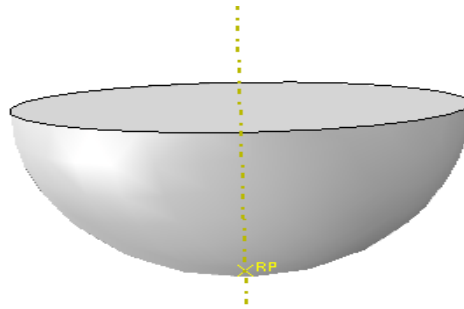
**Fig. 4: Boundary conditions at the bottom face.**

### ***Modeling of the Striker***

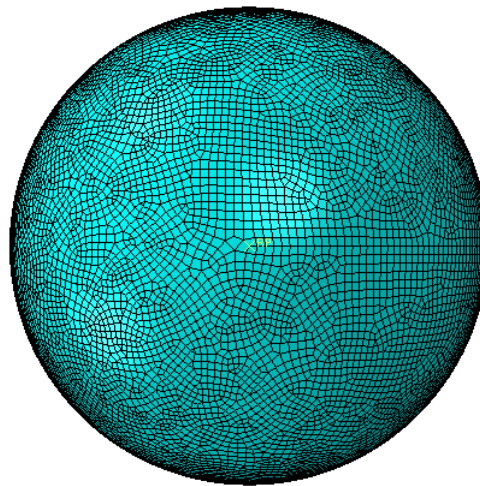
Figure 5 shows the striker which is made of steel. Instead of whole striker, only the striker tip was modeled since striker was modeled as 3D discrete rigid body. Figure 6 shows the modeled striker tip. A rigid body constraint was used for the striker with point mass/inertia engineering features. The mass of the actual striker was assigned to the reference point of the modeled striker. Figure 7 shows enlarged view of the mesh on the striker. The striker was modeled using R3D4 elements which are 3D quadrilateral discrete rigid elements.



**Fig. 5: Actual striker tip.**



*Fig. 6: Modeled striker tip.*



*Fig. 7: Enlarged view of mesh on the striker.*

A displacement/rotation boundary condition was used to restrict the motion of striker. In actual experiment the striker can move only in the z-direction. This condition was applied to the striker so that it will move only in the z-direction, and all other degrees of freedom are constrained. In this model impact only within the elastic limit of the material was considered i.e. no plastic deformation or damage was not considered here. The maximum impact force and contact duration was taken from the simulation to compare with the experimental results.

## RESULTS AND DISCUSSIONS

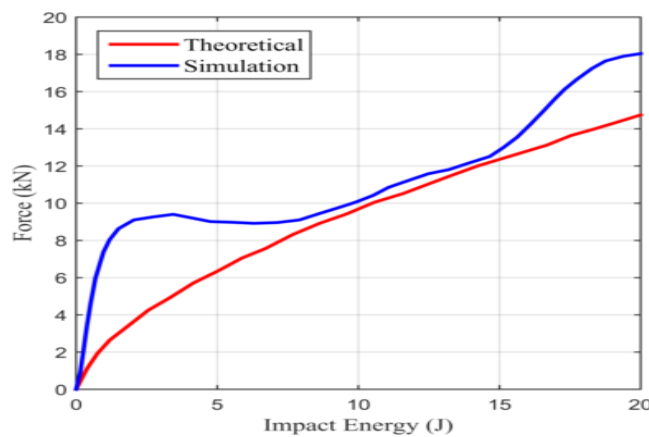
### *Prediction of Maximum Impact Force*

The values of maximum impact force were calculated using equation 8 for different values of impact energy to compare with the values found from the simulation. Figure 8 shows the variation of maximum force with respect to different impact energy. It is observed from Figure 8 that, the maximum impact force from theoretical and simulation are very close for the impact energy between 8J to 15J. But deviation occurs if the impact energy is less than 8J or greater than 15J.

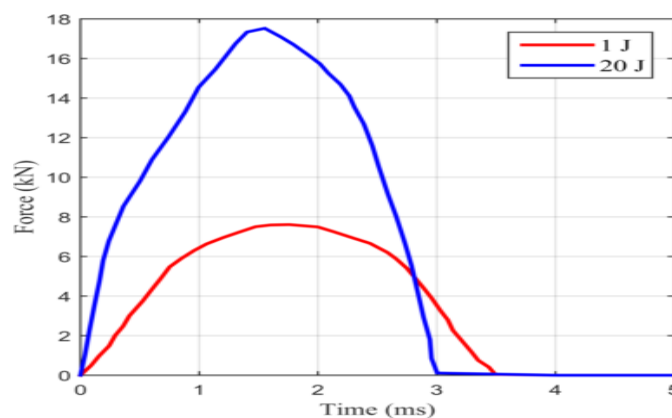
**Maximum impact force vs impact energy**

Impact energies were gradually increased starting from 1J to 20J in the simulation. Impact force increases gradually with time up to a certain limit and then decreases. This happens because of the change in motion of the striker. Just before the striker hits the target plate, the kinetic energy of the striker is maximum and at that moment the impact force is zero. During impact, the kinetic energy of the striker decreases gradually and impact force increases accordingly. When the

kinetic energy of the striker after the impact is zero, the impact force is maximum at that moment. The impact force is then reduced again because the striker bounces back to its original position. The maximum impact force for 20J impact energy is much higher compared to 1J impact energy and also the contact duration decreases as the impact energy increases which indicates that the striker bounces back faster for higher impact energy. (See *Figure:-9*)



**Fig. 8: Variation of maximum impact force with energy.**



**Fig. 9: Impact force v/s time.**

***Variation of displacement with time***

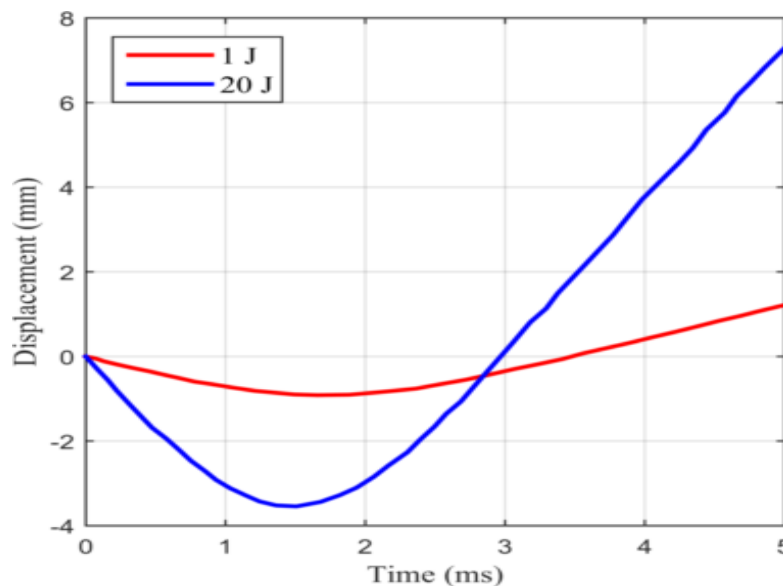
Figure 10 shows the displacement vs time history of the striker. It is observed from this figure that, when the striker hits the target plate the displacement is zero which is the considered reference position for the striker. As the striker hits the target plate, the displacement of the striker increases in the negative direction (it is considered that the striker hits at the top of the target plate).

When the velocity of the striker becomes zero, the maximum striker displacement is achieved at that time. After then, the striker bounces back to its original position i.e. the striker moves to upward position. A positive value of the displacements

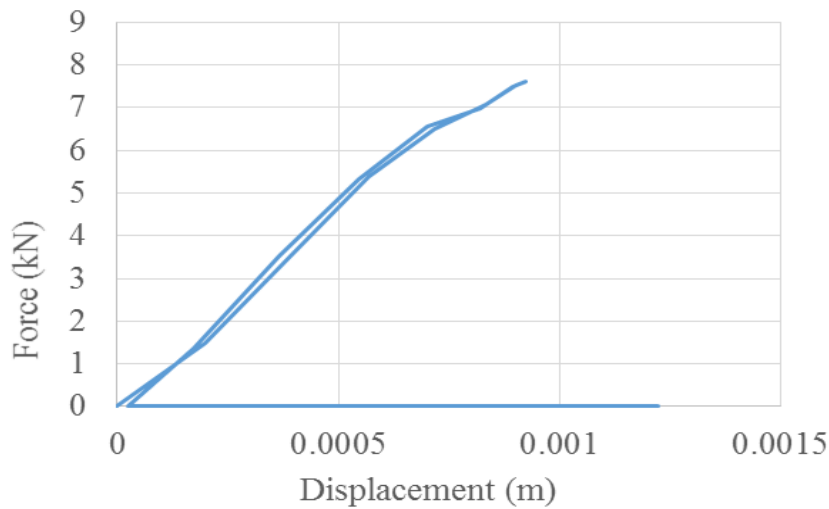
indicate that the striker is no longer in contact with the target plate.

***Variation of force with displacement***

Figure 11 shows the force vs displacement curve for 1J impact energy. This graph shows that the impact force increases with displacement and reaches to its maximum value when the striker velocity is zero. Then the impact force started to reduce to zero when the striker loses its contact with the target plate and remains zero for the remaining period. Although, the impact force vs displacement for both impacting and bouncing back of the striker should be the same, it is found from this graph that they are not exactly same but almost same.



***Fig. 10: Displacement v/s time.***



**Fig. 11: Force v/s displacement for 1J energy.**

## CONCLUSION

An analytical solution to predict the maximum force during impact is formulated in this paper based on Hertz's contact law and nano-indentation property of a material. Numerical simulation is carried out to predict the impact force on polypropylene material. Different energy level is considered ranging from 1J to 20J during impact and it is found that the maximum impact force predicted from the analytical solution and simulation are very close for the impact energy 8J to 15J and deviation occurs other than this range of impact energy.

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