Modeling and simulation of Charpy impact test of maraging steel 300 using Abaqus

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Abstract. This work emphasizes the modeling and simulation of Charpy impact test to evaluate fracture energy at different pendulum velocities of armor maraging steel 300 using ABAQUS. To evaluate the fracture energy, V-notch specimen is fractured using the Johnson and Cook Damage model. The Charpy impact tests are of great importance related to fracture properties of steels. The objective of this work is to present absorbed energy variation at pendulum velocities of 5 m/sec, 6 m/sec, 7 m/sec and 9 m/sec in addition to stress distribution at v-notch. Finite Element Method of modeling for three dimensional specimens is used for simulation in commercial software of ABAQUS.

1. Introduction

The Charpy impact test is the standard test to determine the fracture toughness of materials and the ductile materials absorb more energy at higher test temperatures while at lower test temperature this energy is found lower. For the steels, as the temperature lowers, they lose ductility and failure occurs by cleavage resulting lower absorbed energy. The absorbed energy in the Charpy test is considered as fracture toughness of the materials. The shifting of the energy absorption curve from lower shelf to upper shelf indicates transition from ductile to cleavage failure. Norris et al investigated the dynamics of Charpy V-notch test on uniformly hardened solid [1]. The changes in the flow strength and strain rate are observed to be main factors for energy absorption. Mathur et al conducted tests on V-notch specimens with impact loading and after investigation they found that stress and strain are strongly influenced by surface. The plane strain condition is found in good agreement on the regions close to specimen centre [2]. The impact loadings are frequently encountered in high speed projectile in defense and automotive applications. This work presents the finite element modeling and simulation of V-notch Charpy impact test over the range of the velocities according Johnson and Cook (J-C) model using Abaqus software. Johnson and Cook have developed an empirical relationship which is used to find the strain rate sensitivity of metallic materials. Johnson-Cook constitutive model is famous for metals [3]. This model is most widely used to solve the problems of sudden loading [4-8]. Since, the Johnson-Cook equations are simple and easy to find out the required constants, hence this model is extremely popular. The V-notch in the Charpy specimen acts as pre-existing crack which enhances the possibility of the brittle failure of the metals [9]. Small quantity of alloying elements is added to armour steel. This steel is hardened followed by tempering to produce tempered martensite in the microstructure. The tempered martensite gives the optimum desired properties in the steel. Hence, this steel is utilized to manufacture the preventive sheets of tanks used for battle and also used in armour vehicles. Therefore, it is necessary to understand the reliability of armour 300 steel...
under the range of impact velocities. The armour steel 603 is investigated by Xu et al in the range of strain rate and temperature 0.0001 to 4500 per second and 288 K to 873 K respectively. They observed that thermal softening is playing important role over the strain rates and work hardening [10]. The damage evolution of armour homogeneous steel was analyzed by Whittington [11].

2. Theory of the model

The specimens for the study of impact behavior were modeled in Abaqus Explicit software. The dimensions of the specimens are taken according to ASTM E23 standard. Johnson and cook constitutive models are used to simulate the impact behavior.

![Figure 1. Schematic of Charpy impact of specimen [15].](image)

The ductile failure and viscous plastic deformation is studied simultaneously by Johnson – Cook model. The results of this model are observed close to results produced in analytical method by Hopperstad [12]. This model is best suited for the deformation at higher strain rates. According to Johnson – Cook model, the equivalent stress is expressed by the following expression

\[
\sigma_{eq} = \left[ P + Q (\varepsilon^p)^n \right] \left[ 1 + R \ln (\varepsilon^*) \right] \left[ 1 - \left( T^* \right)^m \right]
\]  

(1)

Where, \(\varepsilon^p\) is build up plastic strain, \(n, m, P, Q\) and \(R\) are constants and \(\varepsilon^* = \varepsilon/\varepsilon_0\).
The relationship between strain and stress triaxiality, temperature and strain rate is given below (Johnson-Cook model).

\[
\varepsilon_f = \left[ S_1 + S_2 \cdot \exp\left( S_3 \cdot \sigma^* \right) \right] \left[ 1 + S_4 \ln\left( \frac{\varepsilon^*}{\varepsilon_f} \right) \right] \left[ 1 + S_5 \cdot T^* \right]
\]

(2)

Where

- \(\varepsilon_f\) is failure strain,
- \(\sigma^* = \sigma_{\text{eq}}/\sigma_{\text{eq}}\) indicates ratio of stress triaxiality and \(S_1 - S_5\) denote material dependent constants and \(\sigma_{\text{eq}}\) indicate average stress. The first term in the equation (2) predicts that the strain decreases by increasing equivalent stress. The second term shows the influence of strain rate on the ductility of the material. The last term in the equation represents influence of temperature on the ductility of the material.

In this model, the failure is considered due to strain concentration in the plastic region and the fracture occurs after reaching to a particular value of the stress. The values of the constants \(S_1-S_5\) are determined using tensile tests [12, 16-18].

3. Finite Element mesh

Figure 1 shows the schematic of Charpy Impact Test including the specimen and striker.

![Figure 1. Schematic of Charpy Impact Test.](image)

**Figure 2.** Abaqus image of Charpy specimen model meshed with hexagonal finite elements.

The span length is maintained 40 mm as per standards of Charpy test. The striker was modeled as discrete rigid body with mass of 30 kg and the specimen is considered to be deformable. Fine mesh was generated at the notch region and coarse mesh in the remaining part of specimen. The whole model is divided into small elements and finite element technique is used for analysis. The 3D model was meshed with Hexagonal elements. The global sizes of elements were kept at 0.3 and 1 with the curvature control of 0.1. The shapes of elements were taken hexagonal with free technique in the mesh control. The process of analysis of 3D stress is selected explicit. In the Element type tab of mesh module (ABAQUS) hourglass elements were selected. The whole model was meshed with 128667 elements. The mesh density is
maintained more around the notch region with global size of element of 0.3 and 1 global element size is used for remaining part of model. The model exhibit 91641 elements in the length of 20 mm around the notch only. The convergence test is also carried out before selecting the mesh.

Boundary conditions: Two boundary conditions were created which are as follows:

Boundary Condition 1. The striker and specimen were modeled as a line contact. The nodes are free to move in the x and z-directions but are restricted in the y-direction. ($U_x = U_z = UR_x = UR_z \neq 0, U_y = 0$).

Boundary Condition 2. The Striker is allowed to move only in the vertical direction ($U_x = U_z = UR_x = UR_y = UR_z = 0, U_y \neq 0$).

4. Simulation conditions

The Crack propagation after impact was simulated using the Johnson – Cook material model and Johnson-Cook failure model. Element deletion was done using the Johnson – Cook failure model. This simulation was utilizing Abaqus explicit time integration and the runtime of 2 milli seconds was taken for analysis. The four impactor velocities of 5, 6, 7, and 9 m/s are taken to fracture the Charpy specimen. The notch depth is also varied from 2.0 mm to 2.30 mm. The damage constants are used from the literature. The density (7999.429 Kg/m$^3$), young’s modulus (192 GPa) and poison’s ratio (0.283) are used from ASM handbook [12].

5. Results and discussions

The variation of absorbed energy with time for impactor velocities 5, 6, 7 and 9 m/s are shown in the Figure 3. It is observed that the lower shelf of impactor velocity of 6 m/s (red curve) is above the lower shelf of impactor velocity of 5 m/s (black curve) while the upper shelf of impactor velocity of 6 m/s (red curve) is below the lower shelf of impactor velocity of 5 m/s (black curve). Similarly, the lower shelf of impactor velocity of 7 m/s (blue curve) is above the lower shelf of impactor velocity of 6 m/s (red curve). The same type of shifting of lower shelf and upper shelf is observed for the impactor velocity of 9 m/s. Therefore, it is observed that by increasing velocities of impactor the lower shelf shift towards the higher absorbed energy and smaller time of interval while the upper shelf shift to the lower absorbed energy. The portions (turning region) of the energy versus time plots between the upper and lower is called transition region. The transition region indicates transition of the ductile to cleavage failure of metal. Due to transition of failure mode from ductile to cleavage, the absorbed energies are lowered for higher impactor velocities. Hence, it is clear that the higher impactor velocities promote the quick transition of the failure mode from ductile to cleavage.
The dynamic stress concentration factors are calculated by the ratio of maximum stress to nominal stress and the data is tabulated in table 1. The values of stress, displacement and impact energy with the varying velocities of maraging steel 300 are shown in the table 3.

**Table 1.** Dynamic stress concentration factor and velocities.

| Velocity (m/s) | Dynamic stress concentration factor |
|---------------|-------------------------------------|
| 5             | 1.329                               |
| 6             | 1.499                               |
| 7             | 1.571                               |
| 9             | 1.707                               |

**Table 2.** Parameter of Johnson and Cook constitutive model for maraging steel 300.

| Johnson Cook plasticity model, Parameter [13] | Johnson Cook failure model, Parameter [14] |
|-----------------------------------------------|--------------------------------------------|
| A                | 758.423 MPa | D1                      | -0.09                      |
| Velocity (m/s) | Max Von Mises stress (MPa) | Max Displacement (mm) | Impact energy absorbed (kJ) |
|---------------|----------------------------|-----------------------|-----------------------------|
| 5             | 1513                       | 9.6                   | 40.2                        |
| 6             | 1556                       | 11.66                 | 39.4                        |
| 7             | 1498                       | 13.7                  | 38.7                        |
| 9             | 1588                       | 17.77                 | 37.75                       |

**Table 3.** Variations of stress, displacement and impact energy with the velocities of maraging steel 300.

**Figure 4.** The variation of stress with impactor velocities of maraging steel 300 in the Charpy impact test. (A) 5, (B) 6, (C) 7 and (D) 9 m/s.
Figure 5. The legends showing the values of stress with varying impactor velocities of maraging steel 300 in the Charpy impact test. (A) 5, (B) 6, (C) 7 and (D) 9 m/s.

Figure 6. The legends showing the values of magnitude of displacement with varying impactor velocities of maraging steel 300 in the Charpy impact test. (A) 5, (B) 6, (C) 7 and (D) 9 m/s.

The distribution of stress is shown in figure 4. The variation of stress with the impactor velocity of 5 m/s is presented in figure 4 (A). The stress field is found extended by increasing velocity of impactor to 6 m/s as shown in the figure 4 (B). The similar extension of stress field is observed for the increased velocities of 7 m/s and 9 m/s which are revealed in figure 4 (C) and (D). The maximum stress values are shown in the figure 5 (A), (B), (C) and (D) for the impactor velocities of 5, 6, 7 and 9 m/s. The figure 5 represents that the maximum values of stresses and these values decrease by increasing velocity of the impactor. The magnitude of displacement in the x-direction at different velocities is presented in the figure 7. The displacement distribution is found extended as shown in the figure 7 (B) in comparison of figure 7 (A) for the impactor velocities of 6 and 5 m/s respectively. The similar nature of extension of displacement is observed in the figure 7 (C) and (D) for the impactor velocities of 7 and 9 m/s. The magnitudes of displacements are shown in the figure 6 (A), (B), (C) and (D) for the impactor velocities of 5, 6, 7 and 9 m/s. The maximum values of displacements are observed increasing by increasing the impactor velocities as shown in the figure 6.
The displacements versus time plots are shown in the figure 8 for the different impactor velocities. The plot (black curve) of displacement versus time for the 5 m/s is below the displacement curve (red curve) for the impactor velocity of 6 m/s. While the displacement curve (pink curve) for the impactor velocity of 9 is above the blue curve which is drawn for the impactor speed of 7 m/s. It summarizes from the figure 8 that the displacement versus time curve shifts towards the larger displacements for the higher values of impactor velocities. And these higher values of the impactor velocities enhance early failures of metal. The initial part of the displacement vs time curve is parallel to the time axis but later lifts sharply towards the displacement axis to reach to the maximum value. This parallel portion of the curve represents the incubation time in which material does not fracture but it becomes ready to start the crack propagation. The end of displacement vs time plot indicates the completion of the fracture.

Figure 7. The variation of displacement with impactor velocities of maraging steel 300 in the Charpy impact test. (A) 5, (B) 6, (C) 7 and (D) 9 m/s.

While the portion of the displacement vs time plot from the end of incubation time to the just before the end point represents the continuation of the fracture of the steel. The incubation period is found smaller for the higher impactor velocities. The figure 9 represents the plot of energy absorbed versus time for the varying notch-depth of Charpy impact test. The black, red and blue colored plots are of notch depth 2.0 mm 2.15 mm and 2.30 mm respectively. As the energy versus time plot (black) of 2.0 mm notch depth is above the plot (red) of 2.15 mm notch depth and plot (red) of 2.15 mm notch depth is above plot (blue) of
2.30 mm. It indicates that the absorbed energy lowers by increasing notch depth. This lowering in absorbed energy is possibly due to lowering in state of triaxiality.

The variation of Charpy energy with the displacement of element in x-direction is shown in the figure 10. The Charpy energy plot vs displacement of impactor velocity of 9 m/s is below of Charpy energy plots of impactor velocities of 5, 6 and 7 m/s which are shown in the figure 10. Therefore, it is observed that the Charpy energy vs displacement plots shift towards the lower observed energy and larger displacement for the higher values of impactor velocities.
Figure 9. Charpy energy vs time plot of maraging steel 300 for varying notch-depth.

Figure 10. Absorbed energy vs displacement plot of Charpy impact test of maraging steel 300 for varying impactor velocities.
6. Conclusions

1) It is found that absorbed energy increases by increasing impactor velocities in lower shelf region while it is found lowered in the upper shelf region of energy versus time plot.
2) The absorbed energies are lower in the upper shelf due to transition of the failure mode from ductile to cleavage.
3) The maximum values of displacements are observed increasing by increasing the impactor velocities as shown in the figure 6.
4) The figure 5 represents that the maximum values of stresses decrease by increasing velocity of impactor
5) The displacement vs time plots rise sharply for higher impactor velocities.
6) The incubation time lowers for the higher velocities as shown in the displacement vs time plot as shown in the figure 8.

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