Numerical Simulation of the Effects of Strain Hardening Exponent with and without Strain Rate Sensitivity of Material on Normal Elastic Plastic Impact

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Abstract. The material behavior selection is an important factor governing the structural response analysis of transverse impact problems, such as impact force, indentation and local elastic plastic deformation. In the present paper, the effects of strain hardening exponent (n) and strain rate sensitivity (m) on the transient response were investigated for low impact velocity by the aid of finite element simulation using the Abaqus Software. Investigated parameters are impact force histories, indentation and plastic strain (PEEQ). Results showed that the effect of n values on required parameters is more pronounced, unlike strain rate sensitivity which has not a significant influence. As well, material behavior selection is essential for an accurate local plastic strain analysis.

1. Introduction
Impact-caused plasticity is a crucial problem in mechanical contact and has a significant role in the industry sector for engineering applications, a means to improve the performance of mechanical systems such as the fatigue resistance and the operation effectiveness of mechanisms in contact-mode. Most of the research involving impact problems of solids have been aligned on dynamic indentation, approached by the quasistatic indentation conditions in the case of low velocity. From this point of view, several contact models of impact problems have been proposed and made available (Thornton [1], Stronge [2], Kogut and Etsion [3], Abrate [4]) based on the pioneering work of Hertz [5], a classical work that has been developed by Goldsmith [6] and Johnson [7], giving a broad study of elastic plastic impact of solids, particularly the plastic deformation inside the contact, whose purpose is to describe clearly the impact force-indentation relationship. Although the efficiency of all these contact models for impact problems, the impact velocity choice should be made cautiously, especially with intermediate and high impact velocity. There is a lack of investigation studies addressing impact velocity, in this respect, we addressed this problematic on our previous work Kriflou et al [8] and we...
concluded that with high velocities of elastic plastic transverse impact of sphere on beam, the plastic deformation can be generated in areas outside the contact zone and the beam can be plastically deformed by bending. we also investigated numerically the applicability of contact model based on Hertz theory with high impact velocity Kriflou et al [9], the investigation showed that for accurate prediction of transient impact response, it is recommended to analyze with low velocity. The dynamic problems investigation in contact-mode stressed the importance of material behavior, such as strain hardening and strain rate sensitivity effects for accurate description of deformation behavior. Park and Pharr [10] used a numerical modelisation of spherical indentation of elastic-plastic material, to discuss the hardening behavior effects on elastic-plastic transition regime of indentation. Lee and Komvopoulos [11] studied numerically the dynamic spherical indentation of elastic-plastic solids, and investigated the strain rate hardening exponent effects. The aim of the present study is to investigate the effects of strain hardening exponent with and without strain rate sensitivity of material on normal spherical impact of elastic-plastic beam by the aid of finite element simulation. A three-dimensional finite element model of the problem is modeled using Abaqus software. The results interpretation of investigated parameters such as impact force histories, indentation and plastic strain (PEEQ), have shown that the transient response of transverse spherical impact of elastic-plastic beam is more pronounced with the increasing of n values, strain rate sensitivity consideration has no significant effect on the transient response results for low impact velocity.

2. Numerical modeling

2.1. Constitutive models

Deformation in the elastic-plastic beam is described by Two constitutive models. The first model is an elastic-plastic strain hardening model, described, respectively, by the following stress-strain constitutive equation:

\[ \sigma = E\varepsilon, \quad \sigma < \sigma_{yb} \]  
\[ \sigma = \sigma_{yb} \left( \frac{\varepsilon}{\varepsilon_y} \right)^n = K\varepsilon^n, \quad \sigma \geq \sigma_{yb} \]  

where \( \sigma \) is the stress, \( \varepsilon \) is the strain, \( \varepsilon_y = \sigma_{yb}/E \) is the yield strain, \( K \) is strain hardening coefficient with \( K = \sigma_{yb}/\varepsilon_y^n \) and \( n \) is the strain hardening exponent.

The second model is an elastic-plastic strain hardening model with strain rate sensitivity by multiplying the strain hardening law by a term like \( \dot{\varepsilon}^m \), as indicated in the following constitutive equation:

\[ \sigma = K\varepsilon^n \dot{\varepsilon}^m \]  

where \( \dot{\varepsilon} \) is strain rate and \( m \) is strain rate sensitivity exponent. \( n \) values were considered to be varied in the range of 0.2–0.5. The strain rate sensitivity \( m \) of material will be determined from the yield strength of Q345 steel at each strain rate in the following way:

\[ m = \frac{\ln\left(\frac{\sigma_y}{\sigma_{y0}}\right)}{\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)} \]  

given the lack of the yield strength at each strain rate experimental data, we based our choice from Shibo et al [12] who used Split Hopkinson Press Bar (SHPB) experiment data of Q345 steel to determine strain rate sensitivity, the value found is \( m = 0.021 \).

The material properties of the beam and sphere are given in tables 1.

The input true Stress-logarithmic Strain curve used in ABAQUS is shown in Figure 1.
Table 1. Material properties of the beam and sphere

| Property                        | Magnitude |
|--------------------------------|-----------|
| Beam Q345                       |           |
| Density, $\rho_b$ (kg/m$^3$)    | 7820      |
| Mass, $m_b$ (kg)                | 10.929    |
| Elastic modulus, $E_b$ (Mpa)    | 210000    |
| Yield stress, $\sigma_{yb}$ (Mpa)| 345      |
| Poisson's ratio, $\nu_b$       | 0.3       |
| Strain hardening exponent, $n$ | 0.2, 0.25, 0.3, 0.45, 0.5 |
| Strain rate hardening exponent  | 0.021     |
| Sphere Gr15                     |           |
| Density, $\rho_s$ (kg/m$^3$)    | 7800      |
| Mass, $m_s$ (kg)                | 1.4       |
| Elastic modulus, $E_s$ (Mpa)    | 208000    |
| Yield strength, $\sigma_{ys}$ (Mpa)| 2550     |
| Poisson's ratio, $\nu_s$       | 0.3       |

Figure 1. Perfectly plastic and true Stress-logarithmic Strain curve of Q345 with $n$ values varied in the range of 0.2–0.5

2.2. Analysis description
The three-dimensional finite element model we have developed in our previous work Kriflou et al [9] using Abaqus software, has been used for the present study. Figure 2 shown the meshed quarter model for simplification and reduction time CPU reasons.
Figure 2. 3D Meshed quarter model by ABAQUS

For accurate results of investigated parameters, the mesh was made denser and consistent in an area around the contact region. The beam and sphere are composed from the eight-node linear hexahedral elements with one integration point (C3D8R). The length of the edge of the smallest elements was 0.1mm and the total elements number of finite element model is 450257. Dimensional detail of the beam and sphere are shown in Table 2.

Table 2. Dimensional detail of the beam and sphere

|                |          |
|----------------|----------|
| H. Depth       | 27.8 mm  |
| B. Width       | 60 mm    |
| L. Length      | 780 mm   |
| R, Radius of the sphere | 35 mm    |

3. Results and discussion

The plastic deformation remains the main important parameter to analyse strain hardening effects with and without strain rate sensitivity. Figure 3 represents the equivalent plastic strain (PEEQ) for an elastic perfectly plastic and hardening materials. As it is seen, for an elastic perfectly plastic behavior, the plastic strain distribution is less important and not focused below the contact area with a maximum PEEQ of 2.156% (Figure 3a). Integrating hardening with strain hardening exponent $n=0.2$ has made PEEQ distribution important, homogenous and below the contact region with a reduction of maximum PEEQ value valued at 1.732% (Figure 3b). An increase in the strain hardening exponent decreases the maximum PEEQ value, for $n=0.5$ the maximum PEEQ has a value of 1.257% (Figure 3c). The strain rate sensitivity consideration $m=0.021$ has no profound influence on plastic strain, we are noticing a maximum PEEQ value of 1.246% (Figure 3d).

Figure 3. Plastic strain (PEEQ): elastic perfectly plastic (a); Hardening $n=0.2$ (b); Hardening $n=0.5$ (c); Hardening $n=0.5$ and $m=0.021$ (d), $v_0 = 1$m/s

The strain hardening effects on the contact response can be interpreted through the impact force histories. Figure 4 shows impact force results for $v_0=1$m/s at different strain hardening exponents $n$ varied in the range of 0.2–0.5 with and without strain rate sensitivity $m$. In comparison with elastic perfectly plastic impact force response, we can clearly see that the impact force increases steeply with strain hardening exponent, an increase in $n$ boost the impact force response. As well as the equivalent plastic strain (PEEQ) results interpretation, strain rate sensitivity consideration doesn't make a deep effect on impact force response.
Figure 4. Impact force histories at different strain hardening exponent with and without constant strain rate sensitivity $(\dot{m}=0.021)$, $v_0 = 1 \text{m/s}$

Figure 5 shows the FEM accumulated permanent indentation comparison as a function of impact velocity. The accrued permanent indentation of the elastic perfectly plastic FEM solution increases nearly linearly and reached a maximum value of 0.13mm, whereas in the hardening case with strain hardening exponent $n=0.2$, the accumulated permanent indentation behaves almost constant with a maximum value of 0.034mm. This is due to the strain hardening exponent effect on mechanical properties which makes material behavior more resistant and can better absorb impact.

Figure 6 shows the von mises stress for elastic perfectly plastic and hardening materials, the stress distribution in case of elastic perfectly plastic was found to be propagated through the thickness, whereas in case of hardening with strain hardening exponent $m=0.2$, the stresses were focused near the contact area, which gives us an accurate interpretation of the local deformation. In addition, the visual comparison of cases at contact region, tells us that the geometric deformation of the impacted area is more pronounced with an elastic perfectly plastic behavior than that with strain hardening exponent.
Figure 6. Von mises stress distribution of the FEM Elastic perfectly plastic solution and FEM Hardening solution, $v_0 = 1\text{m/s}$

4. Conclusion
In this article, spherical impact of strain hardening beam with and without strain rate sensitivity was investigated, we have used a three dimensions finite element model that was developed in our previous work using Abaqus software. The present work interprets results of investigated parameters such as impact force histories, indentation and plastic strain (PEEQ) for a better analysis of strain hardening and strain rate sensitivity effects on structural response of the beam, which have shown that transient response of transverse spherical impact of elastic-plastic beam is more pronounced with the increasing of $n$ values and no significant influence of strain rate sensitivity consideration. For all, a hardening material behavior with strain hardening exponent selection is recommended for accurate prediction of transient response analysis in particular local plastic deformation.

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