Title: A Computational Comparison of High Strain Rate Strength and Failure Models for Glass

Authors: Timothy G. Talladay
Douglas W. Templeton

¹US Army Tank-Automotive Research, Development, and Engineering Center,
6501 E. 11 Mile Rd, Warren, MI 48397, USA

Paper ID: 13963473
A Computational Comparison of High Strain Rate Strength and Failure Models for Glass

Computational studies are performed using the recent Holmquist-Johnson glass model and the earlier Johnson-Holmquist brittle material model. Although the JH-2 model has been adapted to provide reasonably accurate predictions for soda-lime glass, the Holmquist-Johnson model was developed specifically to replicate the behaviors of glass. Simulations of rod impact on borosilicate glass using these two models are compared to experiments involving impact of mild steel rods and borosilicate glass at ca. 540 m/s. The material constants were adjusted to attain similar strength and damage responses at this impact velocity. In this manner, some light can be shed on the difference in the mechanisms of these two models. The models are compared and contrasted in penetration-time, penetration resistance, dwell, and the evolution of visual damage phenomena. The limitations of both models are discussed and the need for more experimental data to corroborate simulations is apparent.
Computational studies are performed using the recent Holmquist-Johnson glass model and the earlier Johnson-Holmquist brittle material model. Although the JH-2 model has been adapted to provide reasonably accurate predictions for soda-lime glass, the Holmquist-Johnson model was developed specifically to replicate the behaviors of glass. Simulations of rod impact on borosilicate glass using these two models are compared to experiments involving impact of mild steel rods and borosilicate glass at ca. 540 m/s. The material constants were adjusted to attain similar strength and damage responses at this impact velocity. In this manner, some light can be shed on the difference in the mechanisms of these two models. The models are compared and contrasted in penetration-time, penetration resistance, dwell, and the evolution of visual damage phenomena. The limitations of both models are discussed and the need for more experimental data to corroborate simulations is apparent.

INTRODUCTION

Modeling impact on brittle materials such as ceramics and glasses has been a topic of interest for many years. Suitable material models and associated constants have been proposed by many researchers, however accuracy across a broad range of impact conditions is still not always achievable. Glasses, including soda-lime-silica and borosilicate, are widely used for protection when transparency is desired. The phenomenon of fracture, fragmentation, and total failure are complex and are still not fully understood.

In 1994, Johnson and Holmquist [1] released an improved brittle material model, hereafter referred to as the JH-2 model. This model was used successfully by a number of researchers to replicate projectile impact into glass [2 – 4]. In 2011, Holmquist and Johnson [5] developed a material model specifically for glass, hereafter referred to as the HJ model. This model better accounts for characteristics

---

1 US Army Tank-Automotive Research, Development, and Engineering Center, 6501 E. 11 Mile Rd, Warren, MI 48397, USA
that are observed in glass strength, damage, and failure characteristics. This article discusses a computational comparison of the JH-2 and HJ models when applied to borosilicate glass. The computational results are compared to work by Bourne et al. [6, 7] and analysis by Forde et al. [8].

SIMULATIONS

Simulations are conducted to explore the differences between the HJ and JH-2 models for predicting the response of borosilicate glass. There are significant differences between these two models, a few characteristics are location dependent strength, variable shear modulus, and time dependent softening. The reader is encouraged to see Ref. [5] for an exhaustive list and justification for these features.

Bourne et al. impacted borosilicate glass with 9.5 mm diameter, hemispherical-nosed rods. The rods were 95 mm long and impacted the glass samples at 535 to 540 m/s (slightly different velocities are given in Refs. [6–8]). It is important to note that the four x-radiographs presented in Bourne’s work are from separate experiments which were conducted approximately at the same impact conditions.

Simulations are conducted in the Lagrangian hydrocode EPIC and are run in both two-dimensional and three-dimensional axisymmetry. The impact velocity in the simulations is 537 m/s to account for the range of velocities reported in experiments. To better replicate the behavior of glass, highly distorted elements are converted to particles rather than eroded. Although computationally more intense, the flow resistance of the fragments is an important characteristic of brittle material impact resistance [9]. Both the rod and the glass are meshed with a fine, uniform, non-expanding grid. Sensitivity to mesh size is not investigated in this article. The mild steel rod is simulated with the Johnson-Cook strength and damage models, and the borosilicate glass block is modeled with the two subject brittle material models.

The material constants for borosilicate glass under the HJ model were previously derived. Constants were derived for borosilicate glass under the JH-2 model to maintain similar reference strength and failed strength profiles over the range of impact pressures which occur in this simulation. It is difficult to maintain exactly similar strength and failure profiles over a wide range of pressures due to the differences in the forms of strength models. For higher velocity impacts, it is expected that the constants used in this article for the JH-2 model would be inaccurate.

Penetration Depth

In Fig. 1, the rod nose position relative to the front face of the target is given. For the first 40 µs, both models agree reasonably well with the experimental results. However, after 40 µs the JH-2 simulation tracks closely with the experiment, while the HJ model significantly underpredicts the penetration. The glass block appears to be too strong in this HJ simulation. Both models and the experimental results show an increase in the rate of penetration as the glass bulk progressively fails. The point at which this change in penetration rate occurs is different between the two models. The HJ model shows a change in rate near 24 µs, and the JH-2 model shows a more gradual change in rate from 20 to 32 µs. The experimental results do
not appear to show a significant change in rate until 40 µs, however there is likely some experimental error in the results because of the low number of x-ray images and the fact that the x-rays were from different impact events. Regardless, the general trend of increasing penetration rate is visible.

![Graph](image)

**Figure 1.** Rod nose position for the HJ and JH-2 models and experiment.

The characteristics of the nose position velocity of the two models are considerably different. Based on the simulations, the nose position \( p \) can be approximated as a function of time \( t \) by the following linear segments (time in µs, position in mm). The first penetration rate transition in the HJ model seems to be the beginning of widespread failure in the glass block, and the second transition seems correlate to the rod sharpening effect (see Fig. 5) observed by Bourne et al. and the final failure of the glass. The sharpening and second transition in penetration rate are not observed in the JH-2 model.

\[
\begin{align*}
\text{HJ Model:} & \quad p = 0.1077t, \quad 0 \leq t < 24 \\
& \quad p = 0.1845t - 1.8473, \quad 24 \leq t < 75 \\
& \quad p = 0.4184t - 19.382, \quad 75 \leq t \leq 120 \\
\text{JH-2 Model:} & \quad p = 0.1345t, \quad 0 \leq t < 30 \\
& \quad p = 0.4461t - 9.6179, \quad 30 \leq t \leq 120
\end{align*}
\]

Simulations with small changes in impact velocity, less than ±1 m/s, are also performed to determine the effect of numerical instability. The change in the calculated nose position for both models is insignificant, with variations of 1 mm or less.

A series of images of the simulation of this experiment are given in Fig. 2. The simulation images are taken at the same time as the experimental images shown in the Bourne et al. and Forde et al. articles (these images are not shown here).
At 2.8 µs, the nose of the cylinder is deformed and has penetrated approximately 0.5 mm of the glass surface. The glass block has not yet deformed under the load of the impact. Forde et al. note that a cone crack appeared at this time step during the impact. They measured an approximate angle between the cone cracks of 110°. Plotting damage contours shows the formation of what appear to be cone cracks in the simulation, with an included angle of 100° in the HJ model. The JH-2 model does not appear to predict a cone crack.

For both simulations at 30 µs, the rod has started to deform and erode, and cone cracks have started propagating into the glass block. The HJ model shows the beginning of a tensile crack opening at the rear surface, however the JH-2 model shows only deformation of the glass block. Fig. 3 shows the contours of damage (red is failed material) which may show where cracks are likely to occur, as was done by Anderson and Holmquist [10]. In this instance, both models show the general trend that is observed in the experimental image.

At 40 µs, the penetration is substantially different between the two models. The glass cone underneath the rod is still visible in the HJ model. Rather than comminuting the material in front of the penetrator, the HJ model predicts more rod deformation/erosion, while a glass cone underneath the rod maintains substantial strength to resist penetration despite widespread material failure.
The final images in Fig. 2 show the response at 80 µs. At this time step, the JH-2 model better replicates the penetration into the glass. In the HJ model, the glass block is still resisting penetration but moves with the rod. The approximate rod nose position from the experiment is 26 mm, and the JH-2 simulation shows an approximate nose position of 27.8 mm. The final image from the Bourne et al. experiment shows the deformed nose has sheared off the rod. In Fig. 4, the HJ simulation shows parts of the rod breaking off from the nose, while the JH-2 simulation does not show this breakage. From the experiment, the nose was rounded, whereas both the simulations show a relatively flat nose. It is also of interest to note that Bourne noticed the plug/cone failure appearance when testing soda-lime-silica glass (see Fig. 5 from Ref. [7]). He notes that at 60 µs, the plug begins to break up and expand radially. This trend is also noted in the HJ model of Fig 4.
Resistance to Penetration

Although the penetration rates and appearances of the two models are different, it is desirable to know the effect on the resistance of the glass block to penetration. Therefore, simulations are run with the same projectile and target, but with varying impact velocities. The strike velocity-residual velocity ($V_s-V_R$) data from the simulations are given in Fig. 5, along with Lamber-Jonas fit curves. The approximate limit velocities are 430 and 375 m/s for the HJ and JH-2 models, respectively. There is no experimental data to validate the computations, so the actual limit velocity of the glass block is unknown. Forde et al. stated an average penetration velocity of 475 m/s between 40 and 80 µs (impact velocity of 535 to 540 m/s), which is close the JH-2 fit curve. However calculating average penetration velocities over this large range of time may not yield accurate results or correlate to residual velocity.

The overall failure of the glass is dominated by a cone of fractured and failed material. This failure mode is shown in both models (see Fig. 3) and appears to be the case for the experiment as well. As such, the simulations predict a cone of glass spall without rod penetration as low as 400 m/s and 300 m/s for the HJ and JH-2 models, respectively.

Figure 5. Residual velocity as a function of impact velocity.

Dwell-Penetration Transition

Forde et al. estimate that the rod dwells on the surface of the glass, however dwell may be difficult to explicitly determine based on the limited number of images available. Behner et al. [11] identified dwell from reverse-ballistic impact experiments using gold rods and borosilicate glass. They measured dwell until at least 32.4 µs at an impact velocity of 412 m/s. The models in this article do not appear to predict a significant time of dwell. In these simulations, the rod initially
deforms, but there is not significant rod erosion without penetration. Significant penetration (greater than 1.5 mm) appears to begin between 10 to 15 µs in both models. The differences in the rod material and impact velocities between the Bourne et al. and Behner et al. experiments are certainly affecting the dwell time.

Fig. 6 shows the tip and tail positions of the rod for the experiment (gray) and models relative to the undeformed glass block (blue). The rod length for the HJ model decreases substantially faster than the length for the JH-2 model. The tail positions track nearly on the same path, however the JH-2 model nose position is shown to quickly penetrate into the glass, whereas the HJ model does not penetrate as quickly. The final rod length is approximately 87 mm for the JH-2 model and 70.4 mm for the HJ model. Bourne et al. states a reduction in rod length due to erosion and deformation of 10 mm, which means a final length of 85 mm. This length correlates well to the JH-2 model. Note that Fig. 6 presents nose position as a negative value and the tail position as a positive value, with zero representing the strike surface of the glass block. Fig. 1 displayed the rod nose position/penetration as positive for convenience only. The nose positions reported in Figs. 1 and 5 are the same absolute value.

![Graph of rod position vs time](image)

**Figure 6.** Nose and tail positions for the HJ and JH-2 models compared to the experimental values reported by Bourne et al. and the undeformed glass block.

**CONCLUSION**

Simulations were conducted using the Lagrangian code EPIC. The simulations compared the effects of the original Johnson-Holmquist model (JH-2) and the new Holmquist-Johnson glass model (HJ). The simulations were compared to experiments completed by Bourne et al. in which 9.5 x 95 mm mild steel rods were
fired at borosilicate glass blocks. The depth of penetration as a function of time, the penetration resistance, the effect of small variations in impact velocity, and the dwell-penetration transition were investigated.

The rod penetration as a function of time for the HJ model did not agree well with the experimental results, however the JH-2 model did agree well. The glass was too strong in the HJ model, however this case was seen by Refs. [1, 10].

The end quantity of concern for the practical application of a model is a performance number, such as the limit velocity. Despite the lack of experimental data to correlate to the models’ limit velocity estimates, the simulations were still completed. The limit velocities differed by approximately 55 m/s, which may or not be significant. From a practical experimental stance, measuring an accurate limit velocity on brittle materials can be highly variable. The difference of 55 m/s (14.7%) may or may not be significant, depending on the experience of the researcher.

The estimated dwell time given by both models is significantly different than the 40 to 60 µs given by Forde et al. and modeled by Church et al. [12]. The dwell time from these simulations is estimated to be between 5 to 10 µs with significant penetration occurring between 10 to 15 µs. One of the principles of the development of the HJ model was to reproduce dwell, therefore it is assumed that the dwell prediction should be reasonably accurate. The disagreement between the experimental and computational results may partially stem from slightly different definitions of the dwell phenomenon. (See Ref. [13] for discussion on dwell). The JH-2 model more accurately predicted the rod shortening (erosion and deformation) than the HJ model, further suggesting the overly strong glass in the HJ model. The impact velocity is not in the hydrodynamic penetration velocity regime, therefore the material strength is still important [10].

The estimated dwell time given by both models is significantly different than the 40 to 60 µs given by Forde et al. and modeled by Church et al. [12]. The dwell time from these simulations is estimated to be between 5 to 10 µs with significant penetration occurring between 10 to 15 µs. One of the principles of the development of the HJ model was to reproduce dwell, therefore it is assumed that the dwell prediction should be reasonably accurate. The disagreement between the experimental and computational results may partially stem from slightly different definitions of the dwell phenomenon. (See Ref. [13] for discussion on dwell). The JH-2 model more accurately predicted the rod shortening (erosion and deformation) than the HJ model, further suggesting the overly strong glass in the HJ model. The impact velocity is not in the hydrodynamic penetration velocity regime, therefore the material strength is still important [10].

The estimated dwell time given by both models is significantly different than the 40 to 60 µs given by Forde et al. and modeled by Church et al. [12]. The dwell time from these simulations is estimated to be between 5 to 10 µs with significant penetration occurring between 10 to 15 µs. One of the principles of the development of the HJ model was to reproduce dwell, therefore it is assumed that the dwell prediction should be reasonably accurate. The disagreement between the experimental and computational results may partially stem from slightly different definitions of the dwell phenomenon. (See Ref. [13] for discussion on dwell). The JH-2 model more accurately predicted the rod shortening (erosion and deformation) than the HJ model, further suggesting the overly strong glass in the HJ model. The impact velocity is not in the hydrodynamic penetration velocity regime, therefore the material strength is still important [10].

The estimated dwell time given by both models is significantly different than the 40 to 60 µs given by Forde et al. and modeled by Church et al. [12]. The dwell time from these simulations is estimated to be between 5 to 10 µs with significant penetration occurring between 10 to 15 µs. One of the principles of the development of the HJ model was to reproduce dwell, therefore it is assumed that the dwell prediction should be reasonably accurate. The disagreement between the experimental and computational results may partially stem from slightly different definitions of the dwell phenomenon. (See Ref. [13] for discussion on dwell). The JH-2 model more accurately predicted the rod shortening (erosion and deformation) than the HJ model, further suggesting the overly strong glass in the HJ model. The impact velocity is not in the hydrodynamic penetration velocity regime, therefore the material strength is still important [10].

The estimated dwell time given by both models is significantly different than the 40 to 60 µs given by Forde et al. and modeled by Church et al. [12]. The dwell time from these simulations is estimated to be between 5 to 10 µs with significant penetration occurring between 10 to 15 µs. One of the principles of the development of the HJ model was to reproduce dwell, therefore it is assumed that the dwell prediction should be reasonably accurate. The disagreement between the experimental and computational results may partially stem from slightly different definitions of the dwell phenomenon. (See Ref. [13] for discussion on dwell). The JH-2 model more accurately predicted the rod shortening (erosion and deformation) than the HJ model, further suggesting the overly strong glass in the HJ model. The impact velocity is not in the hydrodynamic penetration velocity regime, therefore the material strength is still important [10].

The estimated dwell time given by both models is significantly different than the 40 to 60 µs given by Forde et al. and modeled by Church et al. [12]. The dwell time from these simulations is estimated to be between 5 to 10 µs with significant penetration occurring between 10 to 15 µs. One of the principles of the development of the HJ model was to reproduce dwell, therefore it is assumed that the dwell prediction should be reasonably accurate. The disagreement between the experimental and computational results may partially stem from slightly different definitions of the dwell phenomenon. (See Ref. [13] for discussion on dwell). The JH-2 model more accurately predicted the rod shortening (erosion and deformation) than the HJ model, further suggesting the overly strong glass in the HJ model. The impact velocity is not in the hydrodynamic penetration velocity regime, therefore the material strength is still important [10].

The estimated dwell time given by both models is significantly different than the 40 to 60 µs given by Forde et al. and modeled by Church et al. [12]. The dwell time from these simulations is estimated to be between 5 to 10 µs with significant penetration occurring between 10 to 15 µs. One of the principles of the development of the HJ model was to reproduce dwell, therefore it is assumed that the dwell prediction should be reasonably accurate. The disagreement between the experimental and computational results may partially stem from slightly different definitions of the dwell phenomenon. (See Ref. [13] for discussion on dwell). The JH-2 model more accurately predicted the rod shortening (erosion and deformation) than the HJ model, further suggesting the overly strong glass in the HJ model. The impact velocity is not in the hydrodynamic penetration velocity regime, therefore the material strength is still important [10].

The estimated dwell time given by both models is significantly different than the 40 to 60 µs given by Forde et al. and modeled by Church et al. [12]. The dwell time from these simulations is estimated to be between 5 to 10 µs with significant penetration occurring between 10 to 15 µs. One of the principles of the development of the HJ model was to reproduce dwell, therefore it is assumed that the dwell prediction should be reasonably accurate. The disagreement between the experimental and computational results may partially stem from slightly different definitions of the dwell phenomenon. (See Ref. [13] for discussion on dwell). The JH-2 model more accurately predicted the rod shortening (erosion and deformation) than the HJ model, further suggesting the overly strong glass in the HJ model. The impact velocity is not in the hydrodynamic penetration velocity regime, therefore the material strength is still important [10].

The estimated dwell time given by both models is significantly different than the 40 to 60 µs given by Forde et al. and modeled by Church et al. [12]. The dwell time from these simulations is estimated to be between 5 to 10 µs with significant penetration occurring between 10 to 15 µs. One of the principles of the development of the HJ model was to reproduce dwell, therefore it is assumed that the dwell prediction should be reasonably accurate. The disagreement between the experimental and computational results may partially stem from slightly different definitions of the dwell phenomenon. (See Ref. [13] for discussion on dwell). The JH-2 model more accurately predicted the rod shortening (erosion and deformation) than the HJ model, further suggesting the overly strong glass in the HJ model. The impact velocity is not in the hydrodynamic penetration velocity regime, therefore the material strength is still important [10].

The estimated dwell time given by both models is significantly different than the 40 to 60 µs given by Forde et al. and modeled by Church et al. [12]. The dwell time from these simulations is estimated to be between 5 to 10 µs with significant penetration occurring between 10 to 15 µs. One of the principles of the development of the HJ model was to reproduce dwell, therefore it is assumed that the dwell prediction should be reasonably accurate. The disagreement between the experimental and computational results may partially stem from slightly different definitions of the dwell phenomenon. (See Ref. [13] for discussion on dwell). The JH-2 model more accurately predicted the rod shortening (erosion and deformation) than the HJ model, further suggesting the overly strong glass in the HJ model. The impact velocity is not in the hydrodynamic penetration velocity regime, therefore the material strength is still important [10].

The estimated dwell time given by both models is significantly different than the 40 to 60 µs given by Forde et al. and modeled by Church et al. [12]. The dwell time from these simulations is estimated to be between 5 to 10 µs with significant penetration occurring between 10 to 15 µs. One of the principles of the development of the HJ model was to reproduce dwell, therefore it is assumed that the dwell prediction should be reasonably accurate. The disagreement between the experimental and computational results may partially stem from slightly different definitions of the dwell phenomenon. (See Ref. [13] for discussion on dwell). The JH-2 model more accurately predicted the rod shortening (erosion and deformation) than the HJ model, further suggesting the overly strong glass in the HJ model. The impact velocity is not in the hydrodynamic penetration velocity regime, therefore the material strength is still important [10].
results through weakening of the glass. More experimental data for matching the location dependent strengths would provide better material constants, and therefore produce a more accurate model.

REFERENCES