

## INTERFACE DEFEAT OF LONG RODS IMPACTING BOROSILICATE GLASS

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This paper presents an experimental series that investigates dwell and interface defeat for bare brittle materials without any lateral confinement or cover plate system. Reverse impact experiments with gold rods and borosilicate glass targets with a small Cu buffer on top of the glass were performed. Interface defeat was observed simultaneously with five flash X-rays and a 16-picture high-speed optical camera. Experimental results show that the Cu buffer increases the velocity required for penetration by a factor of  $\approx 2$ . Stable dwell is possible for impact velocities up to nearly 900 m/s; whereas without a Cu buffer, penetration starts at impact velocities  $\approx 450$  m/s with only a short dwell phase after impact.

### INTRODUCTION

The phenomenon of interface defeat, and in particular, the transition velocity from dwell to penetration, is not well understood. Researchers have developed very complicated targets with lateral confinements, backings, and different types of cover plate systems and have attributed interface defeat to a large variety of geometric properties, confinement, and hypothesized mechanics [1-3].

The objective of this work is to investigate dwell and interface defeat for bare brittle materials without any lateral confinement or cover plates except for a small buffer on the interface. This eliminates the effect of target configuration so that dwell becomes more of a material property; and consequently, other target configurations, e.g., cover plate and/or confinement, can be assessed against this "bare dwell" configuration. Another objective is to define very carefully the transition velocity from dwell to penetration. The pressure associated with this transition velocity might be considered to be a fundamental property of the specific material. In a first test series, borosilicate glass has been chosen as a cost-effective brittle material which is also of interest in transparent armor.

## EXPERIMENTAL SET-UP

The borosilicate glass targets were cylindrical with diameter  $D = 21$  mm and a length of  $L = 60$  mm. The material properties are given in Table 1. The rods were made of pure gold (99.99%) and had a diameter of  $d = 1$  mm and a length of  $l = 70$  mm with the following material properties: density  $\rho_P = 19.3$  g/cm<sup>3</sup>; hardness 65 HV5; UTS 220 MPa and elongation 30%. A cylindrical Cu buffer was attached to the glass with a height of 2.5 mm and a diameter from 4 to 5 mm. The purpose of the buffer was to attenuate the initial impact shock and provide ramp stress loading on the glass surface [4]. The reverse ballistic method was used in conducting the experiments. The impact and dwell process was observed simultaneously with five 180 kV flash X-rays, and an IMACON 200 high-speed optical camera that took 16 pictures to visualize failure propagation inside the glass. The test set-up was similar to that described in [5]; only the angles of the X-ray tubes with respect to the target plane were changed. Figure 1 shows the arrangement for the impact tank together with a resulting X-ray image of the dwell process. The tests were performed with a powder gun, using a separating sabot to launch the glass targets.

The time measurements for the flash X-ray pictures are very accurate (to better than  $\pm 5$  ns). Thus, the error for the velocities determined from the X-ray pictures rest in the accuracy of the position measurement, which is in the order of  $\pm 0.1$  to 0.15 mm. The camera pictures allowed a position accuracy, the uncertainties caused mainly by irregularities in the shape of the failure front, in the order of  $< \pm 0.2$  mm.

Table 1. Material properties for borosilicate glass (Borofloat® 33)

Density [g/cm <sup>3</sup> ]	Young's modulus [GPa]	Knoop hardness [kp/mm <sup>2</sup> ]	Poisson's ratio	longitudinal wavespeed [km/s]	transverse wavespeed [km/s]	HEL [6] [GPa]
2.2	64	480	0.2	5.69	3.48	8

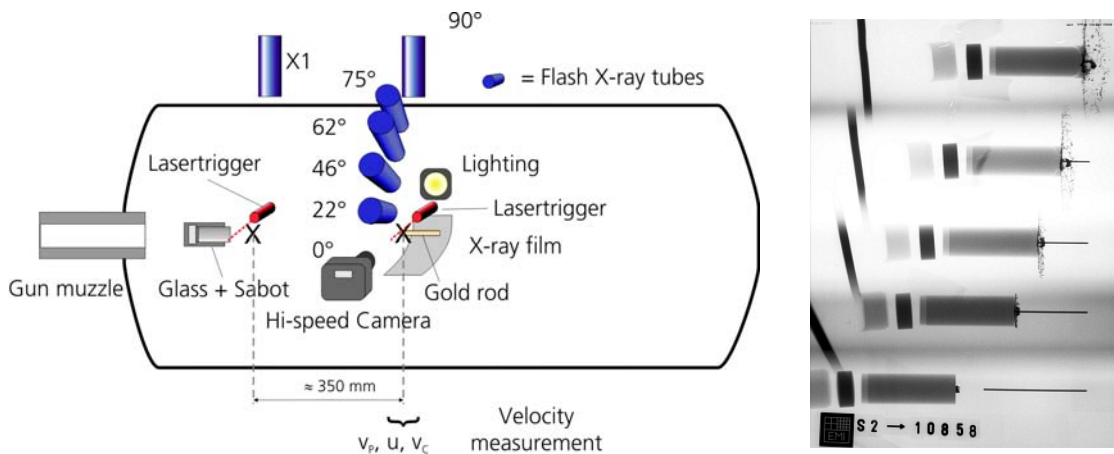


Figure 1. Test-set-up – reverse ballistic method – and resulting X-ray photograph

## RESULTS AND DISCUSSION

A number of experiments showed sustained dwell until the glass hit the Styrofoam support of the rod. Other experiments showed a dwell phase of varying time followed by penetration. Some experiments, where the rod impacts near the edge of the Cu buffer, showed no dwell at all. The experiments are listed by target response in Table 2. Test results are sorted by increasing impact velocity  $v_P$  for each group.

For some experiments in the second group (dwell with penetration) penetration started quite early so that there were enough X-ray images to calculate the penetration velocity  $u$  and consumption velocity  $v_C$  of the rod inside the glass.  $u$  and  $v_C$  were calculated by a linear regression of the position and length of the rod inside the glass over the trigger time of each X-ray image. This was also done for the experiments with no dwell.

Target resistance  $R_T$  was calculated from the well known Tate equation with the  $u$  and  $v_C$  values and with a penetrator strength  $Y_P = 0$ . In case of dwell,  $R_T$  was calculated from  $v_P$ , which represents a lower bound on  $R_T$ .

The camera pictures provided an optical assessment of overall glass failure during dwell and can be used to determine the position of the failure front inside the glass. The region where the glass becomes opaque is interpreted as failed.

Table 2. Experimental results

Exp. No.	Yaw [°]	oc [mm]	$v_P$ [m/s]	$u$ [m/s]	$v_C$ [m/s]	Target response	$R_T$ [Gpa]	$d_{Cu}$ [mm]
-	-	-	-	-	-	-	-	-
10850	0.9	1.9	583±1	-	(= $v_P$ )	sust. dwell	3.28	4
10853	0.9	1.0	649±5	-	(= $v_P$ )	sust. dwell	4.06	4
10854	1.8	0.6	720±1	-	(= $v_P$ )	sust. dwell	5.01	4
10858	0.3	0.8	782±3	-	(= $v_P$ )	sust. dwell	5.90	5
10862	0.4	1.7	890±5	-	(= $v_P$ )	sust. dwell	7.64	5
10852	1.6	1.9	616±2	-	-	dwell + pen.	-	4
10856	1.8	1.6	770±3	-	-	dwell + pen.	-	4
10861	0.6	2.0	816±5	426±17	369±22	dwell + pen.	1.12	5
10860	0.7	1.1	821±3	487±8	330±4	dwell + pen.	0.79	5
10859	0.5	0.8	837±4	464±10	357±11	dwell + pen.	0.99	5
10863	1.6	0.5	882±4	-	-	dwell + pen.	-	4
10851	0.2	2.0	611±2	302±11	301±5	no dwell	0.77	4
10857	0.9	1.6	784±5	431±4	337±7	no dwell	0.89	4
10855	2.6	1.8	794±7	437±14	337±9	no dwell	0.88	4

Yaw: combined horizontal and vertical yaw

oc: off-centre impact

$d_{Cu}$ : diameter of copper buffer

### Sustained Dwell Experiments

Figures 2 and 3 show the X-ray images and optical pictures for two experiments at different  $v_p$  where sustained dwell was established. Each figure captures the dwell process at an early and a late stage with the corresponding picture pairs taken at nearly the same time after impact.

The X-ray images appear to show an axial component in the radial expansion of the deflected gold rod. However, this is due to "optical" distortion as these images are taken outside the focal plane of the X-ray. The optical pictures show that the deflection produces a nearly perfect radial expansion.

An interesting observation for the optical pictures is that there is only a small failed region of the glass (about  $\frac{1}{2}$  a target diameter) near the impact surface, while most of the glass length stays intact for the complete dwell process. This effect is also described in [7]. When dwell occurs, some of the X-ray images reveal a circular, symmetric crack in the glass for the failed region of the glass (see Fig. 3), which can occur quite early during the interaction. Clearly, the glass sustains dwell. Whether the region under the rod is failed or intact cannot be definitively discerned from the photos. We plan to address this question with further testing in the near future.

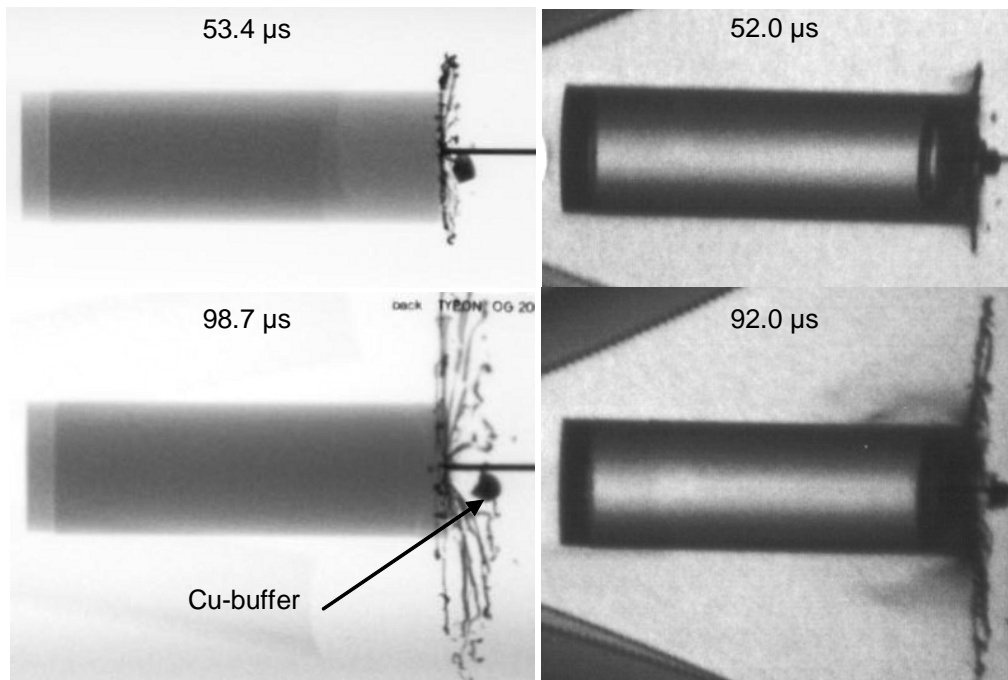


Figure 2. X-ray images (left) and camera pictures (right) for Exp. 10850 ( $v_p = 583$  m/s); times after impact

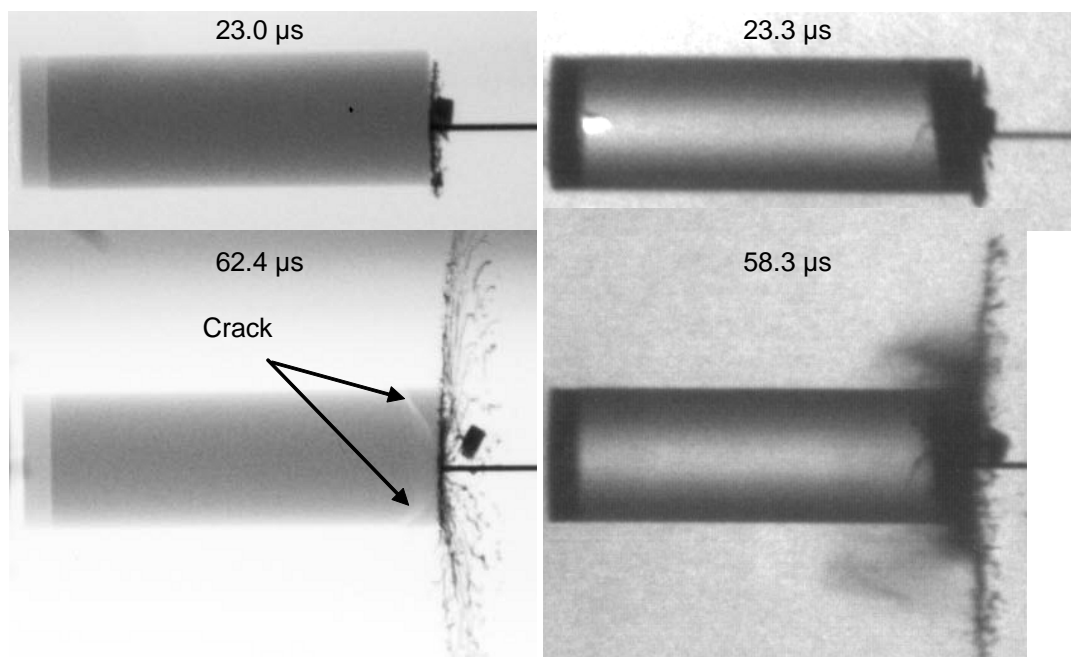


Figure 3. X-ray images (left) and camera pictures (right) for Exp. 10862 ( $v_p = 890$  m/s); times after impact

### Dwell with Penetration

Figure 4 shows an experiment with dwell followed by rod penetration. Again the optical pictures show that during dwell the failed region of the glass is quite small but when penetration starts, the failed zone of the glass expands.

As mentioned earlier, the position of the failure front inside the glass can be determined from the optical pictures. This is illustrated in Figs. 5 and 6 – together with the position of the rod tip – for sustained dwell, and dwell with penetration, respectively. For both cases the failure front stops at around 10 mm inside the glass as long as dwell is present. In case of dwell with a penetration phase, the failed region starts to grow as or shortly after penetration of the rod starts. The distance between the failure front and rod tip also increases for the penetration phase, while it is nearly constant for the dwell phase.

While penetration of the rod inside the glass is a very linear (steady-state) process for all observed experiments, the propagation of the failure front shows an erratic non-linear behavior for the  $v_p$  range concerned here. Consequently, failure front velocities were not calculated for this experimental arrangement. Failure front velocities for very similar experiments are described in [8].

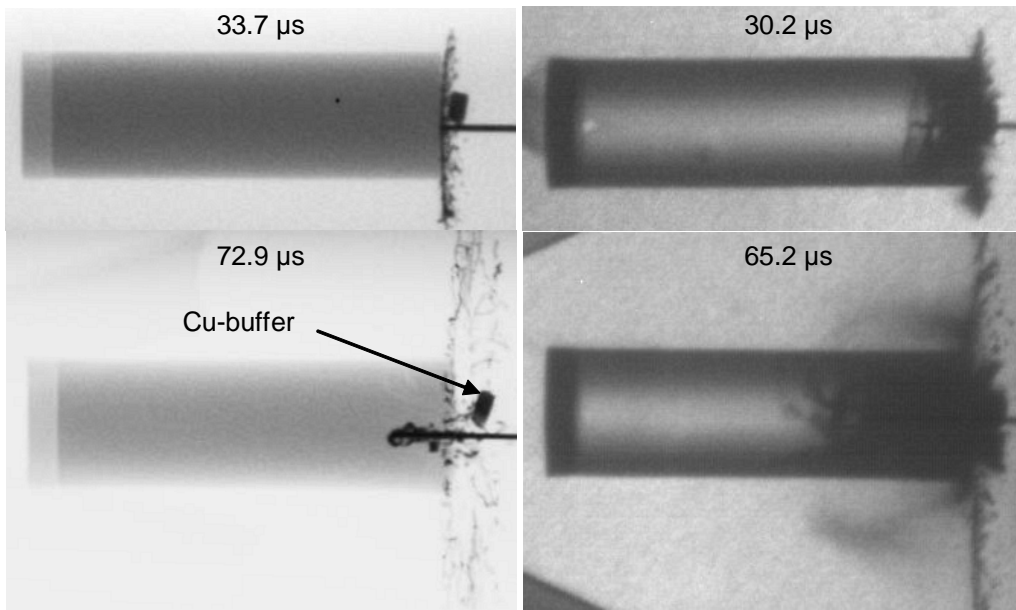


Figure 4. X-ray images (left) and camera pictures (right) for Exp. 10861 ( $v_p = 816$  m/s); times after impact

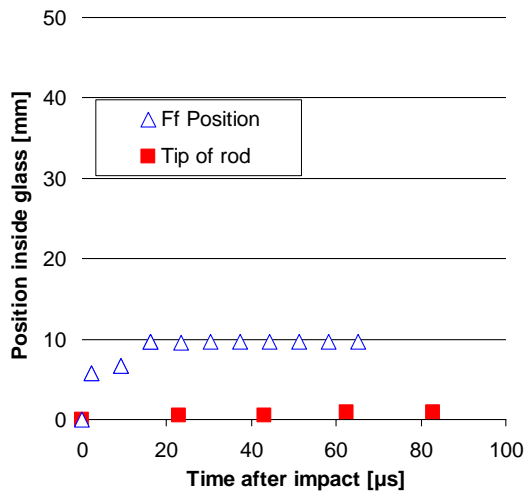


Figure 5. Failure front (Ff) and rod position inside glass after impact (Exp. 10862,  $v_p = 890$  m/s)

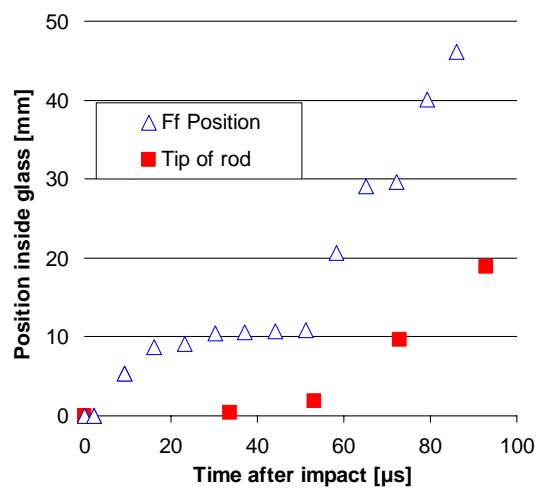


Figure 6. Failure front (Ff) and rod position inside glass after impact (Exp. 10861,  $v_p = 816$  m/s)

## Influence of Cu-buffer

The Cu cylinder enables the glass to withstand penetration at much higher impact velocities than without a buffer material attached. The buffer reduces the impact shock of the rod and provides ramp stress loading on the glass surface. With some experiments showing no dwell at all (due to off-centre hits), penetration of the glass is observed for as low as  $\approx 600$ -m/s impact velocity. In similar experiments conducted in [8], but without the Cu buffer, penetration could be observed at impact velocities as low as 450 m/s.

With the Cu buffer, the experiments show that stable dwell can be produced up to nearly 900 m/s. Interestingly, for most of the experiments, the Cu buffer separates from the glass shortly after impact and has no influence on the dwell process itself.

An exact prediction for the transition velocity of this experimental arrangement, so far, cannot be made. Although some experiments at 820 m/s show repeatable transition from dwell to penetration, other experiments – meant to validate the change to penetration without dwell – showed complete dwell instead. This topic will be investigated in a future test series.

However, the results so far validate the tremendous efficiency of the attached Cu buffer in eliminating impact pressure peaks. For the experiments with complete dwell, the target resistance  $R_T$  from the Tate equation can be described as

$$R_T = \frac{1}{2} \rho_P v_P^2 + Y_P \quad (1)$$

Equation (1) can be described as the minimum strength necessary for interface defeat at a certain impact velocity. This leads to values for  $R_T$  up to 7.6 GPa for the highest achieved impact velocities in this series (Exp. 10862,  $v_P = 890$  m/s), a value very close to the HEL of borosilicate glass [9]. Once penetration sets in (for those experiments with transition),  $R_T$  drops dramatically to values around 1 GPa.

## SUMMARY AND CONCLUSIONS

Reverse impact experiments with gold rods and borosilicate glass targets at impact velocities from  $\approx 600$  to  $\approx 900$  m/s were performed. Interface defeat was observed simultaneously with five flash X-rays and a 16-picture high-speed optical camera. A small Cu buffer on top of the glass provided ramp stress loading and isolated the glass from the shock stresses at impact. Experimental results show that the Cu buffer increases the velocity required for penetration by a factor of  $\approx 2$ . Stable dwell is possible for impact velocities up to nearly 900 m/s; whereas without a Cu buffer, penetration starts at impact velocities  $\approx 450$  m/s. When dwell is observed, the optical

pictures reveal only a shallow damage region at the target surface; otherwise, the glass stays intact for most of its length. As discussed earlier, the “damage” at the impact end of the glass may be the result of a donut-shaped region of damage at the outer diameter of the glass target.

Experiments with dwell at the higher velocities show target  $R_T$  values near the HEL of borosilicate glass. It is remarkable that such strengths can be achieved with a brittle material under impact conditions. This suggests that the pressure associated with the onset of dwell to penetration could be the HEL, or a similarly related material property.

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