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SOME OBSERVATIONS ON THE STRENGTH OF FAILED CERAMIC

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ABSTRACT

This article presents some observations on the strength of failed ceramic under conditions of high-velocity impact. Included are results of recent computations that provide good agreement with a variety of test data, as well as an explanation of the techniques used to represent the damage and strength of the ceramic as it transitions from intact to failed material. For most of the examples noted in this article the damage and failed strength are determined from impact and penetration computations, and are not measured directly from laboratory tests. Some direct test data for failed ceramics have been generated and reported in the literature; they tend to show a great deal of scatter, they tend to not cover the range of pressures and other variables experienced during high-velocity impact and penetration, and they are generally not in agreement with the corresponding data obtained from the computations. Some observations are presented to explain some of these apparent discrepancies and to show the relative effects of intact strength, failed strength and damage.

INTRODUCTION

Ceramics are very strong materials, especially in compression. They are well suited for armor applications when subjected to high pressures during impact and penetration. It is generally agreed that ceramic materials exhibit strength after they are failed, and that this strength is pressure dependent. There is not good general agreement, however, about the magnitude of the strength of this failed material. This is due to the lack of test techniques to directly measure the strength of the failed material under the conditions (strain, strain rate, pressure, temperature, particle size, shape, arrangement) of interest. There have been several techniques used to determine the strength of the failed material, but for direct testing of failed material the pressures are generally lower than those experienced in high-velocity impact and penetration. Another approach has been to determine the strength of the failed material by performing computations to match the results of penetration tests by using assumed strength characteristics. This approach also has its problems inasmuch as it requires an accurate description of the intact strength, the damage model and the assumed form of the failed strength. The computational algorithms (finite elements, meshless particles, sliding/contact) must also be accurate. Sometimes the strength of the failed ceramic has been taken to be the only important variable, but the strength of the intact material and the strength of the partially damaged material can also be important. This article presents computational results, test results for high-velocity impact, test results for failed ceramic, together with some possible explanations for these data.

RECENT COMPUTATIONAL RESULTS THAT INCLUDE FAILED CERAMIC

The authors have developed three similar computational models for the response of ceramics subjected to large strains, strain rates and pressures. They include an intact strength, a failed strength, a damage model for the transition from intact strength to failed strength, and a pressure model that includes bulking. This discussion will be limited to these models as they are well understood by the authors and they illustrate some of the issues of interest. The JH-1 model [1] does not soften the intact material during the damage process, but allows it to drop suddenly to the failed strength when the damage is complete ($D = 1.0$). The JH-2 model [2] softens the material gradually as the damage is accumulated ($0.0 < D < 1.0$). The JHB model [3] treats the damage and failed material in a manner similar to that used in JH-1, with the differences being that the JHB model uses an analytic form for the strengths of the intact and failed material, and it allows for a phase change.

Figure 1 shows intact strength (at two strain rates) and two failed strength levels for the JHB model for silicon carbide [4]. The lower failed strength level of $\sigma^f_{max} = 0.2$ *GPa* was determined from computations to match test data [4] and the higher (Walker) failed strength of 3.7 *GPa* is discussed later. The intact strength is well represented by the model and does not exhibit significant softening at the high pressures. This characteristic supports (but does not prove) the assumption of the JH-1 and JHB forms regarding the lack of softening for partially damaged material. Other arguments for this form are that it is well-suited to represent dwell and penetration, it has been used to accurately simulate a range of test data [4], it does not allow gradual softening that can introduce numerical inaccuracies, and it enables the constants to be obtained with a straightforward process.

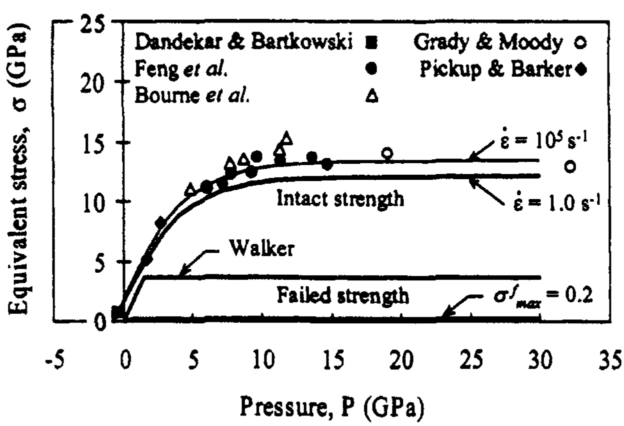

Figure 1. Strength versus pressure for silicon carbide test data and the JHB model.

The top portion of Figure 2 shows interface defeat ($V = 1410$ *m/s*), dwell and penetration ($V = 1645$ *m/s*), and penetration ($V = 2175$ *m/s*) for a tungsten rod impacting a confined silicon carbide target [4,5]. The damage constant ($D_1 = 0.16$) is determined (from the $V = 1645$ *m/s* data) to match the time at which dwell ceases and penetration begins (about 20 μs) and the maximum strength of the failed material ($\sigma^f_{max} = 0.2$ *GPa*) is determined from the penetration rate after penetration begins. There is also good agreement between the computed results and the test data for the molybdenum rod and the various velocities.

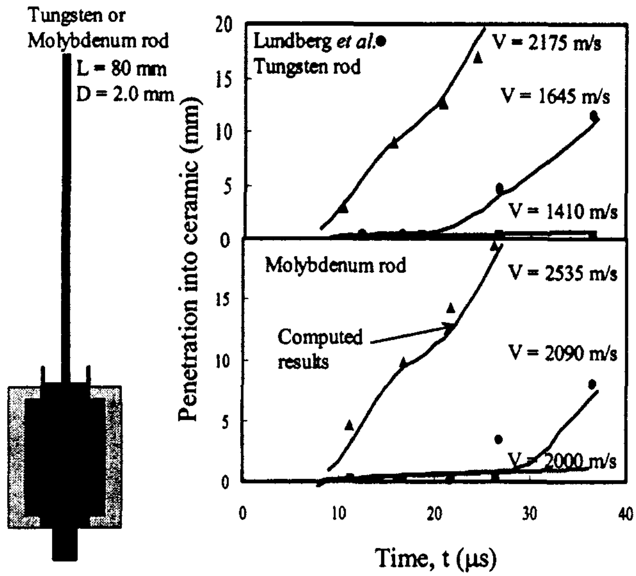

Figure 2. Comparison of computed results and test data for tungsten and molybdenum rods impacting a confined silicon carbide target.

The damage is represented by $D = \Sigma(\Delta\varepsilon_p/\varepsilon^f_p)$ where $\Delta\varepsilon_p$ is the increment of equivalent plastic strain during the current cycle of integration and $\varepsilon^f_p = D_1(P^*+T^*)^n$ is the plastic strain at failure for a dimensionless pressure, P^*, and a dimensionless hydrostatic tensile strength, T^*. The other constant is assumed to be $n = 1.0$ such that the failure strain is a simple linear function of the pressure. It is well established that the ductility increases as the pressure increases, but the form of the relationship is unknown. In a similar manner, the failed strength uses an assumed slope (σ^f vs P^*) for the low-pressure region, and the failure strength is essentially determined by a single constant (σ^f_{max}).

The same constants are used for the computational results in Figure 3, where P is the total penetration and L is the initial length of the tungsten rod. Here, for a different set of tests involving total penetration for a range of higher velocities [6], there is again very good agreement [4]. Computational results are also shown for an assumed case of no failure of the ceramic (such that the intact strength is used for the entire computation), and it can be seen that the computed penetration results are much too low [1]. It is clear from these results that the ceramic does fail, and that the failed strength is much lower than the intact strength. A final set of computed results is for the assumed case of no failure strength and no ductility (the material fails as soon as it experiences plastic strain). Here the penetration is much too high and it has not stopped. This indicates that the ceramic must have some ductility and/or some strength after failure. An intermediate case with ductility ($D_1 = 0.16$ in the damage model), but no failure strength, gives slightly too much penetration for V = 1500 *m/s*, but essentially the same penetration (as for the σ^f_{max} = 0.2 *GPa* computations) at the higher velocities.

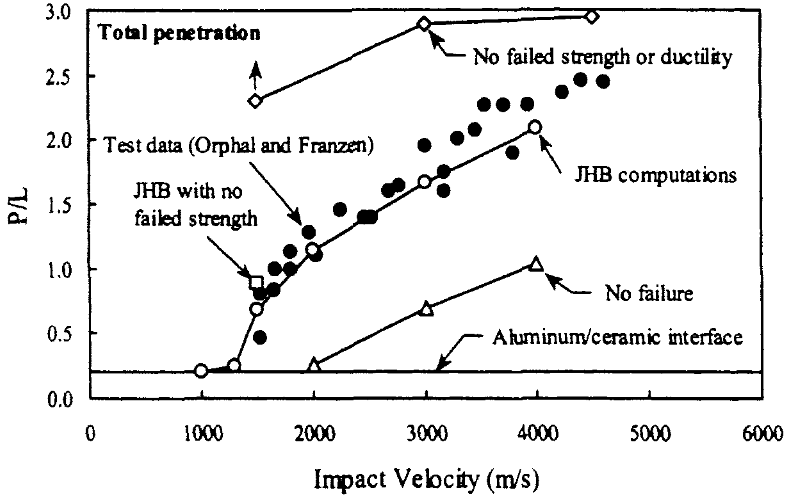

Figure 3. Comparison of computed results and test data for a tungsten rod impacting a confined silicon carbide target at various impact velocities.

A final computation is shown in Figure 4, where a steel projectile impacts and perforates a thin, layered target of silicon carbide over aluminum. Even at the lower impact velocity (670 *m/s*) the agreement (exit velocity) is in good agreement with experimental data [4].

ISSUES AND UNCERTAINITIES REGARDING FAILED CERAMIC

Although the ability to accurately simulate a range of high-velocity conditions is encouraging, there are some issues and uncertainties. Two major assumptions are that the damage model is represented by a single constant (D_1) and the failed strength is essentially represented by two constants (a slope at low pressures and σ^f_{max}). Even simple strength and failure models for metals contain on the order of 10 to 20 constants. It would appear that failed ceramic, with the particle size, shape and arrangement changing under high-pressure deformation, would be at least as difficult to model. It is unlikely that the failed ceramic behaves in as simple a manner as the models assume.

Figure 5 shows some additional computations compared to the same test data as shown previously in Figure 3. The Walker strength model [7] consists of a Drucker-Prager model with a strength cutoff. It is included in Figure 1 and it has a maximum strength of 3.7 *GPa*. This model does not explicitly account for intact material, and therefore, one possible interpretation is that it represents an average of both failed and intact material. It falls between the intact strength and the failed strength for the JHB model. The Walker results in Figure 5 are slightly below the test data, and this is because the constants were determined from the rates of penetration rather than the total penetration. The CTH Eulerian computations presented by Walker were essentially duplicated with Lagrangian EPIC computations performed by the authors.

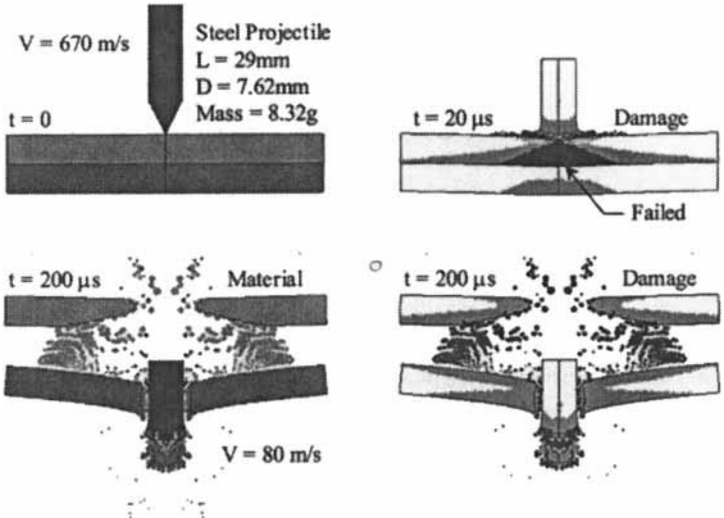

Figure 4. Computed results for a steel projectile impacting and perforating a thin, layered target of silicon carbide over aluminum

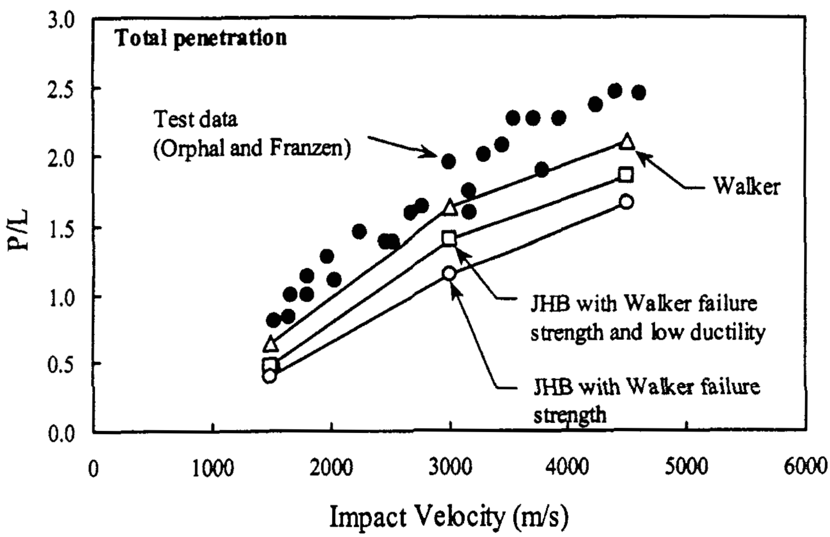

Figure 5. Penetration versus impact velocity for a tungsten rod impacting a confined silicon carbide target, for various computational models.

Even though the penetrating tungsten rod is primarily in contact with failed ceramic material, the damage model and the strength of the intact material have a significant effect. The second set of computations in Figure 5 assumes a JHB type of model, with the intact strength shown in Figure 1, a damage model with D_1 = 0.16, and the Walker model as the failed strength (adjusted to zero strength at zero pressure, and subjected to the strain rate effect). It can be seen that the computed penetration results are much too low, and that the intact strength and ductility have an important effect. The final set of computations uses the same intact strength and the adjusted Walker model for the failed strength, but the ductility is essentially eliminated by using D_1 = 0.001 in the damage model. These results fall between the other two sets of computations, and it appears that the intact strength and the damage model (ductility) have significant and approximately equal effects.

There is a real need for strength data for failed ceramics, especially under the conditions experienced during penetration. Although there have been numerous efforts to generate such data, there are no generally accepted models and constants for failed ceramic under the conditions experienced during penetration. As an example, recent work at Southwest Research Institute [8] examined the strength of two states of damaged/failed silicon carbide, as shown by the two thicker lines in Figure 6. The comminuted material was pre-damaged using a thermal shock procedure and this resulted in a pattern of cracks that weakened the material (although it remained intact). The powder material has much less strength. This tends to illustrate the wide range of behavior that can be attributed to failed ceramic.

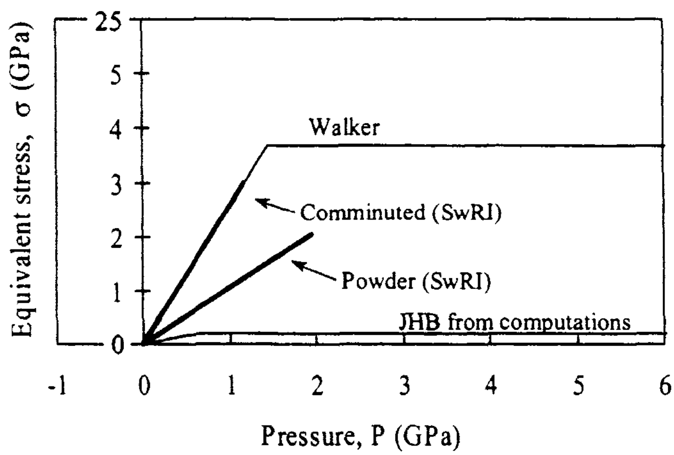

Figure 6. Failure strength versus pressure for various tests and models

The slope of the comminuted material is very similar to that used in Walker's model (b = 2.5), but it was not possible to test to high enough pressures to achieve strengths above about 3.0 *GPa*, or to show a decrease in the slope as the pressure increased. It would appear that this (partially damaged) comminuted material (for pressures up to about 1.0 *GPa*) is again an average of the intact material and the (fully damaged) powder material. Based on the computations in Figure 4, if the intact strength and ductility are included, then the failed strength must be much lower than that provided by the comminuted data.

The most disturbing aspect of the data in Figure 6 is that the strength of the powder material goes to about 2.0 *GPa*, at a slope of about 1.0. This strength of 2.0 *GPa* is significantly larger than the value (σ^f_{max} = 0.2 *GPa*) determined from the computations. One possibility is that there are errors in the computations and/or the models for the intact strength, damage model, pressure model, etc. (which must also be correct for the determined failed strength to be correct). Also, the experimental procedures and analyses were recently developed and there could be issues with the experimental technique and/or the associated interpretation.

Another possibility is that the failed strength is somehow lowered under the conditions that exist during penetration. The simple Bernoulli pressure for tungsten penetration into silicon carbide is 0.78, 3.12 and 12.5 *GPa* for impact velocities of 1000, 2000, 4000 *m/s*, respectively. These pressures are much higher than those generated during the aforementioned tests. The strains and strain rates are also significantly higher during penetration. Even though it intuitively appears that the ceramic could not become much weaker than the powder used in the tests, perhaps the combination of large strains, high stain rates and high pressures could alter the size, shape and arrangement of the particles, thus producing a lower strength. Although it does not appear that the ceramic will melt under these conditions, the possibility has not been eliminated.

Figure 7 shows some responses for the strength as a function of plastic strain and damage, under a constant pressure and strain rate. The JH-1 and JHB models provide instantaneous failure (when $D = 1.0$), and the JH-2 model provides a gradual failure (for $0.0 < D < 1.0$). The authors have chosen to use the JH-1 and JHB forms for the reasons stated previously, although it is possible that the JH-2 form is as good or better. Note that the intact strength and damage for the JH-2 model would be defined differently than for the JH-1 or JHB models. The response for the combined model provides a possible explanation that is consistent with the penetration data, the comminuted and powder data, and the computational results. Unfortunately, there do not appear to be any existing experimental techniques that can be used to produce such data (intact to damaged to failed, under high pressures and deformations).

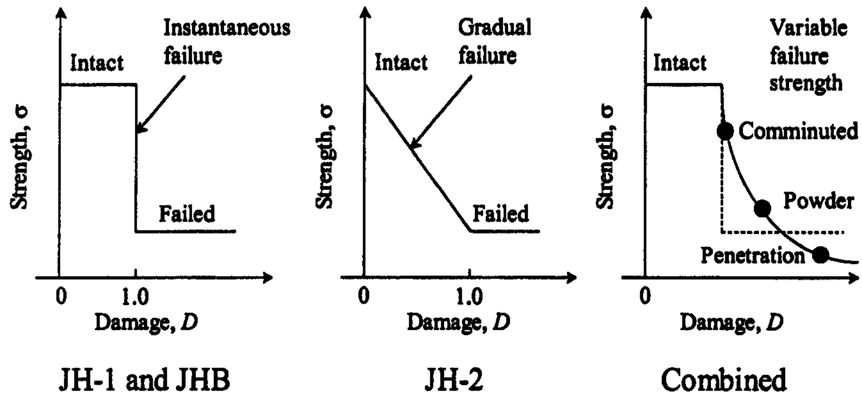

Figure 7. Damage and failure responses for various models

SUMMARY AND CONCLUSIONS

It has been demonstrated that it is possible to accurately simulate a wide range of impact and penetration conditions by using computational ceramic models that include intact strength, damage, and strength of failed material. These computations use a failure strength that is derived from the penetration experiments, however, and this failure strength is not always consistent with data obtained explicitly from failed material. It would appear that this discrepancy is due to errors in the computations, errors in the material models, and/or lack of appropriate data for the damage and failure strength for the conditions experienced under high-velocity impact and penetration.

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REFERENCES

[1]T. J. Holmquist and G. R. Johnson, "Response of silicon carbide to high velocity impact," *J. Appl. Phys.*, **91**, 5858-66 (2002).

[2]G. R. Johnson and T. J. Holmquist, "Response of boron carbide subjected to large strains, high strain rates, and high pressures," *J. Appl. Phys.*, **85**, 8060-73 (1999).

[3]G. R. Johnson, T. J. Holmquist and S. R. Beissel, "Response of aluminum nitride (including a phase change) subjected to large strains, high strain rates, and high pressures," *J. Appl. Phys.*, **94**, 1639-46 (2003).

[4]T. J. Holmquist and G. R. Johnson, "Characterization and evaluation of silicon carbide for high velocity impact," *J. Appl. Phys.*, accepted for publication (2005).

[5]P. Lundberg, R. Renstrom and B. Lundberg, "Impact of metallic projectiles on ceramic targets: transition between interface defeat and penetration," *Int. J. Impact Engng.*, **24**, 259-75 (2000).

[6]D. L. Orphal and R. R. Franzen, "Penetration of confined silicon carbide targets by tungsten long rods at impact velocities from 1.5 to 4.6 km/s," *Int. J. Impact Engng.*, **19**, 1-13 (2000).

[7]J. D. Walker, "Analytically modeling hypervelocity penetration of thick ceramic targets," *Int. J. Impact Engng.*, **29**, 747-55 (2003).

[8]K. A. Dannemann, S. Chocron, A. E. Nicholls, J. D. Walker and C. E. Anderson Jr., "Ceramic phenomenological experiments–compressive strength of SiC," Final Report, Southwest Research Institute, San Antonio, Texas, June 2004 (Revised November 2004).