METHODOLOGY FOR SURVIVABILITY AND DESIGN OF HIGH SPEED PENTROMETERS

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Abstract

This paper describes a methodology for designing high velocity penetrometers based on an integration of simulation and precise experiments. This methodology is typical for that used to design military systems and significantly derisk potential systems before the enter service. An outline description of various *QinetiQ* capabilities is given which could be brought to bear for penetrometer applications in the frame of planetary lander missions.

1 Introduction

Exploration of the planets and asteroids has recently enjoyed resurgence due to the specification of long term goals both by ESA and NASA (ESA Cosmic Vision, 2005; State of the Union address by George Bush, 2004). Additional drivers have been the important basic science questions concerning the Moon, for example, such as whether it possesses a core and whether there is water embedded within the lunar regolith. This has given a focus to innovative research efforts aimed at performing good science on a cost effective basis.

One such idea is the notion of instrumented penetrators which can be embedded into sub–surface layers and perform there a range of *in situ* measurements. In principle this method is simpler in that there is no need for a lander staying on the surface. However, there is the challenge of ensuring that the instrumentation survives the high 'g' loading caused by the impact.

This paper outlines a proposed methodology for the design of high velocity penetrometers, where 'high velocity' is defined as $v_{impact} > 100$ m/s, such that the loading on the penetrator covers the shock regime. This paper will not attempt to address other issues relevant to the design of penetrometers as, for example, power supplies, communications,

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etc., although in these areas *QinetiQ* also has a lot to offer. Rather the paper will focus on how *QinetiQ* expertise can be used to design and test a general survivable penetrometer system. *QinetiQ*'s approach to research on impact physics is now built around the cornerstone of an integrated approach between simulation and experiment. Therefore the hydrocode and material model development has been aimed at providing a predictive modelling capability. Predictive modelling is defined as being within 5% of the experimental result or within the measurement error, whichever is the smaller. The driver for this has been to reduce the number of full scale experiments and the need for more efficient designs based on a thorough understanding of the mechanisms of their operation during impact. For such an integrated approach it is important to have a proper verification & validation route for the hydrocode modelling and thus there is a need for a rigorous and precisely defined experimental programme.

2 General background on loading regimes

It is important to realize that there are a number of impact regimes of relevance to penetrometers. In the low velocity (acoustic) phase, the impact energy is rapidly communicated through the penetrator. In the shock phase the shock is generated at impact because the local flow of the material is supersonic and the energy cannot dissipate quickly enough. In frequency space we effectively have a delta function in the high frequency range. For low velocity penetration (i.e. a few m/s) the projectile undergoes a steady state resistive loading and any wave propagation within the projectile is generally in the acoustic range. For survivability the key is for the components to be protected from any sharp tensile waves, which may cause fracture. Any deformation of the projectile is controlled by the constitutive or stress/strain behaviour of the relevant projectile materials.

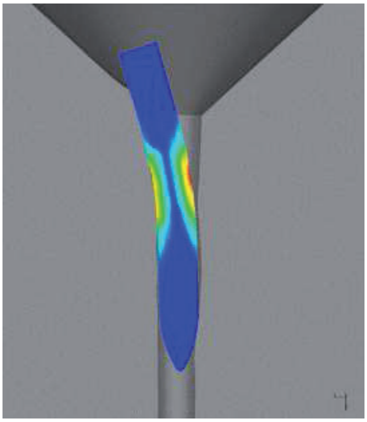

Figure 1: Example of a penetrator being deformed during an oblique impact.

However, when the impact velocity is increased above about 50 m/s the projectile will experience a significant shock wave or pressure discontinuity, which will then reflect at various interfaces inside the projectile, dependent on projectile geometry. In the shock regime the deformation of the material is controlled by the hydrostatics or equation of state. If reflections generate a tensile wave and this exceeds the tensile limit of the material, then that material will fracture through spallation. In order to prevent this it is important to manage these wave reflections by careful choice of materials and geometry. This illustrates the value of an integrated modelling and experimental approach since the wave structures in the material generally impose a complex 3D stress state, which is sometimes counter–intuitive. Once the shock has been dissipated there are still considerable resistive forces to overcome. These can lead to significant projectile deformation and possible break–up, particularly under asymmetric impact conditions, for example due to obliquity, as shown in Figure 1.

3 Description of methodology

The military has developed a range of high velocity penetrator designs over the past 40 – 50 years using well established and mature design methodologies. The key aspect to this approach is to *reduce the risk* throughout the design process so that there is a much higher probability that the full–scale system will function according to the required specification. This approach has been further enhanced to include the recent developments in advanced computational tools (i.e. hydrocodes) to simulate high velocity impact. The integration of simulation and precise experiments is now a fundamental aspect of the design cycle. This has resulted in more emphasis on small–scale experiments allowing more rapid progress through the *Technology Readiness Levels* (TRLs), up to in–service (TRL 8). The following proposes this framework as a methodology for the design of penetrometers. This is not a rigid framework but is expected to evolve after detailed discussions with other team members, in particular taking account of additional constraints.

3.1 Understanding the requirements and constraints

It is absolutely crucial to the success of the programme that the design team understands the requirement specification and all the implications contained within it. Although this is common sense it can be quite challenging to specify a requirement in common technical language that is understood by the design team. This includes everything from using a well defined nomenclature to a consistent set of units, which has been problematic on some previous space missions. If the requirement is not specified properly or understood fully it becomes all too easy to design a system that works but does not do everything it is intended to do.

In addition it is vital that all constraints are defined and recognized. This covers everything from mass and volume constraints to temperature and radiation environment and material requirements. As an example in low temperatures it may be inappropriate to use materials that exhibit a ductile/brittle failure transition at low temperatures, particularly under impact conditions.

It is also vital that the actual science requirements of the mission are properly appreciated, otherwise there is a great risk of developing a survivable system that doesn't function as required. Given that space missions are driven by complex and unique science these must be communicated in a form that is understood in a multi–disciplinary team environment.

3.2 Assessment of outline penetrometer concepts

The next step, having fully defined and understood the requirements, is to propose penetrometer concepts capable of surviving the impact scenario. At this stage these can range from quite conservative and robust 'bullet' type designs to more innovative and high risk/high benefit type designs. As an example one may propose a design almost guaranteed to survive, but which may have a high mass as opposed to a design that is of lower mass, but unproven in the field.

The strategy is then to use advanced hydrocode simulations integrated with small scale precise validation experiments to evaluate this range of concepts to define a 'performance envelope' and assess the limits when the design is likely to fail. These limits would be defined in terms of impact velocity, attitude of impact, obliquity, target strength etc. The key pre–requisites for the success of such an approach are accurate material models covering various regimes of behaviour for all components as follows:

- Hydrostatics or equation of state (EOS)
- Deformation or constitutive response
- Fracture response

This requires efforts in developing accurate material models for the relevant materials within the penetrometer (metals, composites etc.) and the target (lunar regolith, rocks). Experimentally this will require a number of controlled tests to assess the behaviour of components in isolation and within a penetrometer to act as validation for the simulations. These would cover shock, ballistic impact, thermal behaviour etc. Such experiments can be conducted over a range of scales, using advanced instrumentation to measure details of the impact response. The power of the hydrocode simulations is that they were written to address scaling in geometry and since the physics of impact generally scales, they can be used to address the behaviour at full scale. If the simulations can predict these experiments then the general confidence level in the approach is enhanced and the simulation output can provide additional guidance to the penetrometer design and manufacturing teams. This process of integrated simulations and experiments would be used to down–select concepts for full scale trials. This demands rigorous criteria for judging one concept against another and it is recognized that these criteria need to account for much more than just impact survivability. This is where the coordination with other aspects of the mission becomes critical to ensure that a concept isn't selected that proves unfeasible for use in the actual mission. An example is a concept that survives but has too large power requirements for the post impact phase.

3.3 Final assessment of concepts

Having selected a number of concepts for final assessments, these have to be manufactured to high tolerance and tested under full scale impact conditions. In terms of military penetrator systems it is a mandatory requirement to fully test and demonstrate the system before it is accepted for service.

For a penetrometer it is essential for the full system to be rigorously tested through ballistic trials and simulations before it enters service in space. Whilst this does not cover all aspects of the actual scenario such as low temperature and vacuum it would significantly enhance the confidence level that the system also will function when launched into space. An aspect of this testing would clearly involve post test analysis in terms of testing the components after impact. The outcome at this stage would be a full scale penetrometer concept that functions under ambient conditions on Earth over a range of impact conditions.

4 *QinetiQ* capabilities and track record

QinetiQ is a large and extremely diverse organisation covering research ranging from fundamental electronics to pharmaceuticals to explosives and comprises approximately 8700 people on a large number of sites all over the UK. It was formed in 2001 from an amalgamation of the *MoD* research establishments throughout the 1990's. *QinetiQ* owns and has access to a large range of test facilities ranging from the laboratory atom scale right up to a full–up military system. In principle *QinetiQ* is capable of developing a penetrometer design from the concept phase (i.e. TRL 1) right through to the final validation trials (i.e. TRL 7). The following sections outline how various *QinetiQ* capabilities could be utilised in the design and testing of an impact survivable penetrometer. These are focussed to penetrometer survivability and do not include ancillary capabilities such as communications, batteries etc.

4.1 Projectile design

QinetiQ has a full design capability for sabot launching of projectiles of a vast range of geometries, calibres, masses and materials ranging from small to full scale applications and track record stretching over 40 – 50 years in this area. This includes an extensive range of drawing and design offices and precision workshops as shown in Figure 2.

This design capability is backed up by a significant structural modelling expertise capable of predicting the in–bore loadings on a given projectile design during launch as well as the sabot–projectile interactions. In addition there is significant expertise in the assessment and design of thermal barriers, which may be important in the low temperature environment encountered in space and could be used to protect delicate instrumentation.

Figure 2: Extensive precision workshops at Fort Halstead.

4.2 Materials

QinetiQ has extensive expertise and capability in the fabrication, design and testing of a whole range of materials from metals through to composites and also has a capability to manufacture nano–materials. This is backed up by extensive first principles type modelling and state of the art microstructural analysis facilities. *QinetiQ* also has several strategic alliances with various UK universities allowing it to tap into a much broader range of expertise at the academic level.

4.3 Ballistic facilities

QinetiQ has access to a large array of ballistic capabilities covering a wide range of impact velocities and calibres. These impart a range of accelerations on the projectile ranging from a few 'g' up 120000 'g'. An example of one of the ballistic ranges is shown in Figure 3. They are equipped with sophisticated instrumentation techniques such as high speed cameras, data–loggers etc.

In principle the projectiles can be fired into a range of targets such as geological materials and ice. Furthermore *QinetiQ* possesses a large database of projectiles penetrating various target materials in a range of configurations. In addition there is also a rocket test track at Pendine, used for bomb testing, which is capable in principle of firing a spacecraft at a target at several hundred metres per second. *QinetiQ* also has a range of explosive capabilities, which could be used to produce even higher loadings. Most of these facilities are on external ranges which are owned and run by *QinetiQ*, but supported by the *MoD* under a Long Term Partnering Agreement (LTPA). Thus *MoD* support would be desirable in terms of access to the trials sites and the general penetration data being made available to *MoD*.

Figure 3: Example of ballistic trials on QinetiQ *range.*

4.4 High 'g' electronic packages

QinetiQ already has a significant track record in developing and using electronic packages capable of withstanding high 'g' loadings. Bombs comprising electronic fuzing components have been in service for many years and are impact resistant when fired into geological targets up to at least 300 m/s. *QinetiQ* have developed and used a range of electronic instrumentation for high 'g' applications as listed in Table 1, which gives details of the component and the 'g' loading sustained.

36 GHz antenna, receiver and fuze	Tested to 45000 'g'
Dataloggers, 8 channel, 1MHz	Tested to 60000 'g'
MEMs devices (accelerometers, gyros)	Tested to 50000 'g'
MEMs seismometer	Tested to 50000 'g'
MMIC devices	Tested to 20000 'g'

Table 1: Examples of high 'g' tested electronic devices tested by QinetiQ

Most of these devices exist in miniaturized form as shown in Figure 4.

QinetiQ has developed extensive expertise in terms of designing impact resistant systems by the judicial choice of components, as well as methods of mounting and fixing them to the general projectile structure.

4.5 Laboratory impact testing

QinetiQ has access through the Physical & Chemical Solids (PCS) Group at Cambridge to perform controlled high velocity impact experiments. These experiments are coupled to state of the art instrumentation so that the maximum amount of information is extracted, making these tests very useful in defining a validation process for the hydrocode

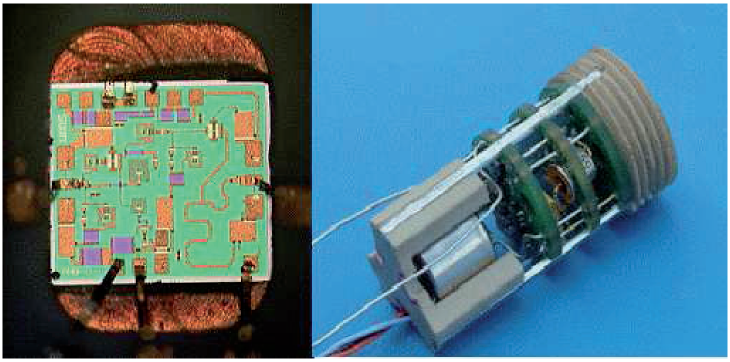

Figure 4: Example of QinetiQ designed electronic devices to survive high 'g' loading – MMIC chip tested to 20000 g (left); communication system and electronic fuze tested to 45000 g (right).

modelling. Much of the instrumentation techniques are portable and thus can be used on external ranges. Examples of instrumentation techniques available are stress and strain gauges, laser interferometry (VISAR), Flash X–ray of internal flow field (digital speckle radiography), as well as high speed photography and spectroscopy.

4.6 Hydrocodes & material model development

QinetiQ uses two main hydrocodes to predict projectile impact and has vast experience of developing and applying them across a multitude of scenarios. The first is the *QinetiQ* hydrocode GRIM, based on an Euler methodology. It is a multi–material hydrocode using advanced and accurate numerical techniques. It can be thought of as equivalent to the US CTH Euler hydrocode, although there are some differences in the numerical scheme, interface treatments etc. The other hydrocode is a *QinetiQ* maintained version of the public domain Lagrangian hydrocode DYNA. The difference between Euler and Lagrange is illustrated in Figure 5.

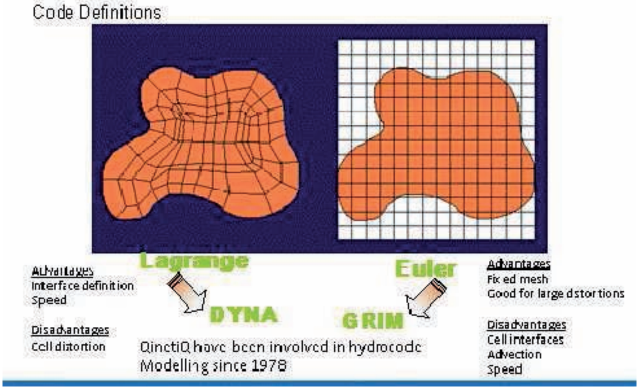

Figure 5: Definition and relative advantages of Euler and Lagrange.

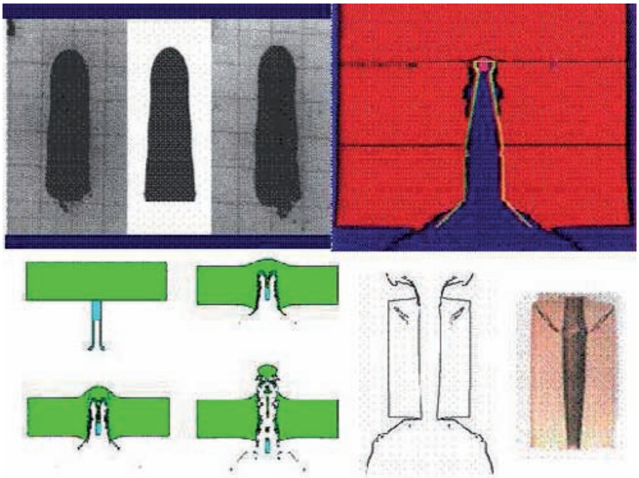

Figure 6: Examples of predictive modelling capability; Explosively formed projectile (top left), Shaped charge penetration (top right), perforation of target (bottom left), Fracture cylinder (bottom right).

A unique feature of this hydrocode capability is the development of advanced material models which have enabled a predictive modelling capability to be developed. These material models are physically based so that all the constants are either derived or measured from basic compression and tension tests. Examples of the success of this approach are shown in Figure 6 for a range of ballistic applications, compared to experiments. These models for isotropic metals are considered fit for purpose by MoD and are now used routinely in both GRIM and DYNA in 2D and 3D computations.

The main effort in developing material algorithms is currently focussed on non–metallic materials, particularly geological materials ranging from reinforced concrete to sand and rock, resulting in the *QinetiQ* Porter-Gould (P–G) model. These new techniques are based on first principles methods using a derivative of molecular dynamics modelling called *Quantitative Structural Property Modelling* (QSPM). The input information they require is simply the chemical constituents and their relative volume fractions.

A full description of QSPM techniques is given in Porter (1995). Recently it has been applied to silica based materials (Church et al., 2006). The essence of the method is to place the molecules in a fixed box, apply an atomic potential (i.e. Lenard Jones) to them, and then calculate the resultant P, V, T, E response. This is output in a SESAME tabular form and in principle is readily transferable between different hydrocodes. There are three caveats to this method: the first is that one has to be careful in interpolating between the 3D EOS surface for a code since the gradients are used to calculate sound speeds, for example. The second is that at the extremities of the tabulated data, extrapolations must be performed to prevent the model from causing instabilities. The third is that to provide a physically based unloading model for these materials in a SESAME form is quite a challenge and still the subject of current research.

The success of this technique has been very impressive in terms of predicting shock Hugoniot curves as demonstrated in Figure 7 for a range of geological materials, including the different forms of silica. The model is also capable of predicting phase changes between the different crystal forms of silica. The P–G model has also been used in a precursor attempt to predict shock Hugoniot data for ice in various forms (Stewart and Ahrens, 2005), as shown in Figure 8. Further work is required to characterize the many different forms of ice, but this represents an extremely promising start.

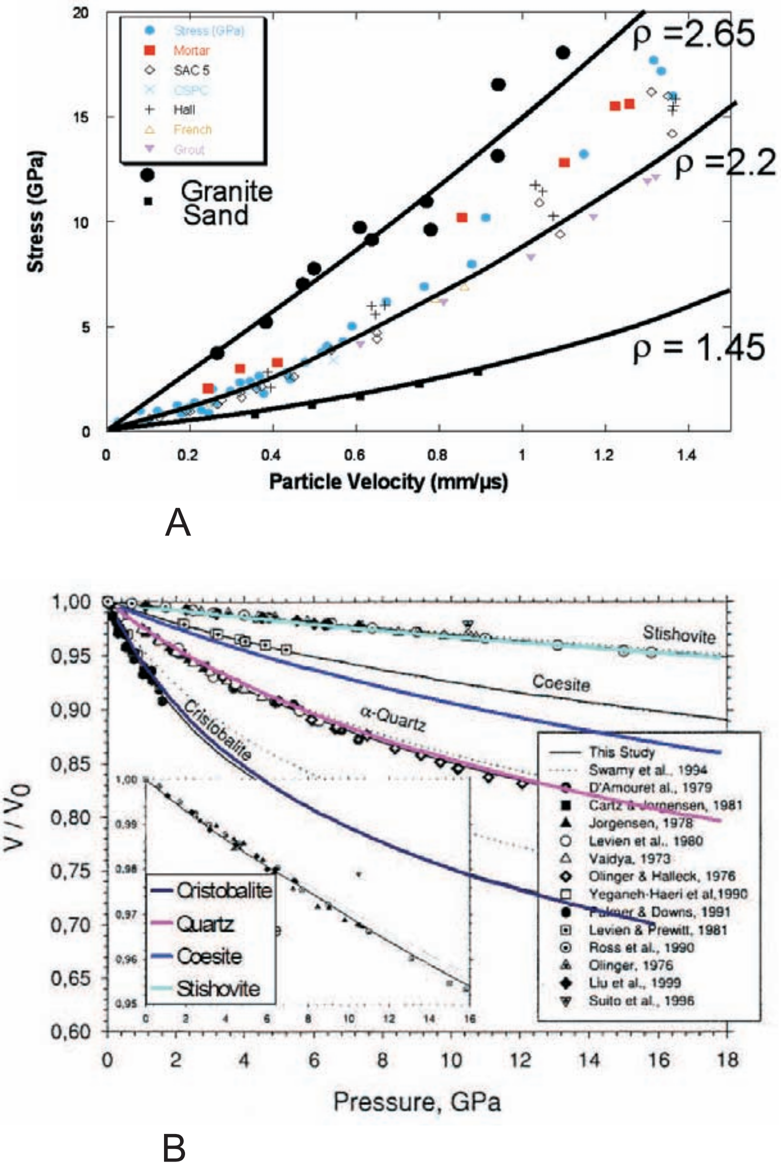

Figure 7: Comparison of QinetiQ Porter–Gould model with pressure volume data for different silica crystal forms (top) and shock Hugeniot data for various geological materials (bottom).

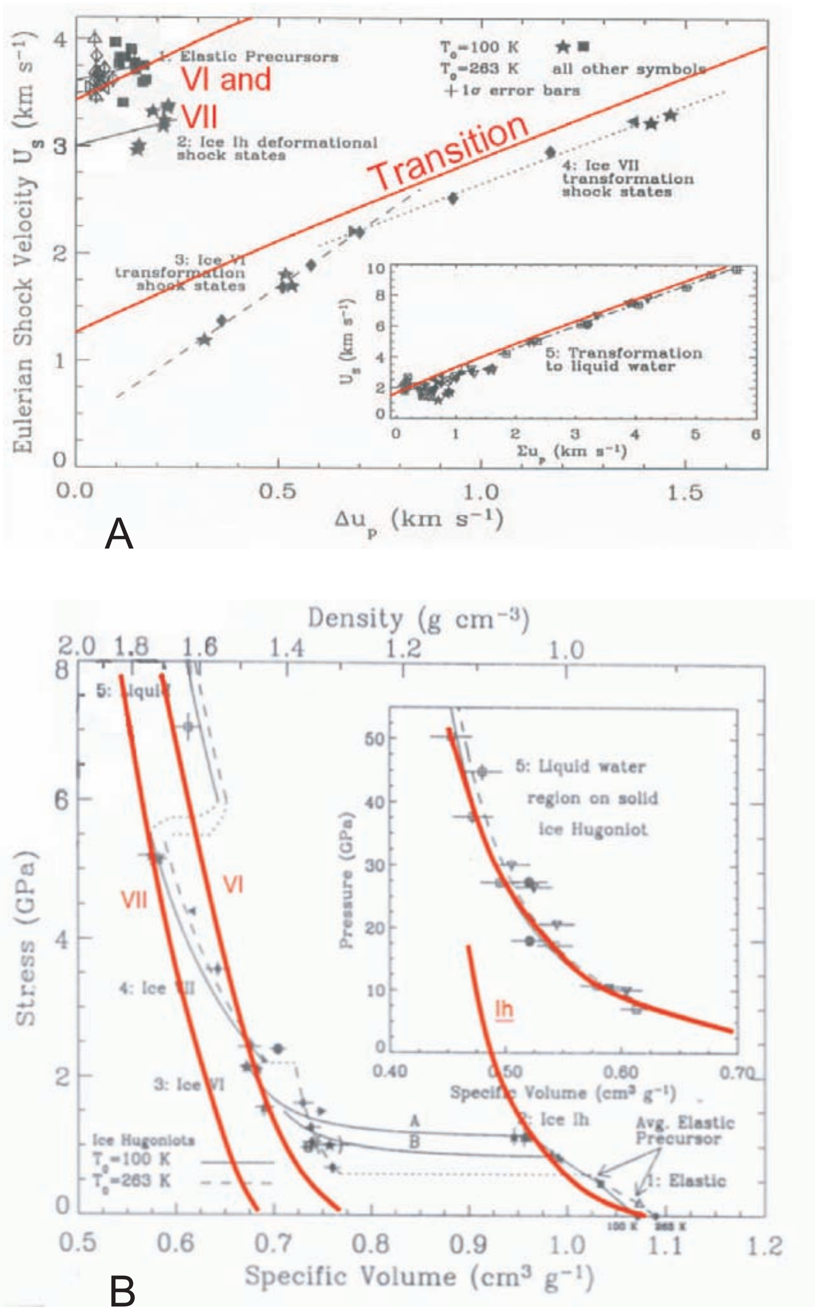

Figure 8: Comparison of QinetiQ Porter–Gould model with pressure volume data for different silica crystal forms (top) and shock Hugeniot data for various geological materials (bottom).

An exciting development of the Porter–Gould approach is its extension to the constitutive response for geological materials, based on a general polymer behaviour, originating from studies on spider silk. The success of the approach is illustrated in Figure 9 for the prediction of the stress/strain curve during a constrained compression test (GREAC cell). This is significant since most previous models must be fitted to these data, whereas the P–G model is predicting it from a first principles approach. As stated this is still the subject of current research efforts within *QinetiQ* focussing on strain rate dependency effects.

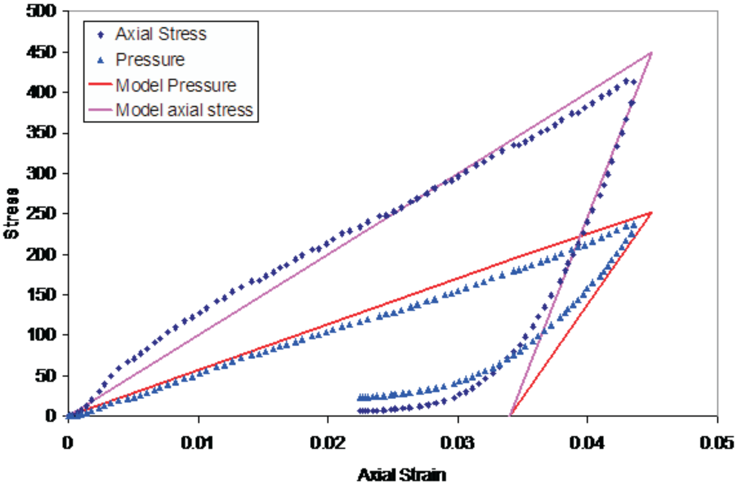

Figure 9: Comparison of Porter–Gould model with constrained compression data for concrete.

5 Conclusions

1. A methodology for the design of penetrometers has been defined, based on a significant derisking of concepts through the TRL chain as used routinely to design military systems.
2. An integrated approach between simulation and precise experiments is essential for the success of this methodology.
3. *QinetiQ* has extensive ballistic ranges and a proven capability in the development of electronics under high 'g' loading.
4. *QinetiQ* has considerable expertise in hydrocode modelling of impact and material and fracture models.

5. The *QinetiQ* Porter–Gould model is a completely novel approach to the prediction of geological materials over a range of strain rate regimes.
6. All this expertise can be brought to bear on the design of high velocity penetrometers for planetary surface applications.

Acknowledgement

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