Executive Summary

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1 INTRODUCTION / OVERVIEW

Rising space debris populations have been recognized as a significant issue for the space community. A breadth of mitigation methods have been assessed such as moving satellites to safe long-term orbits at the end of their active life or disposing of them via re-entry either actively or within reasonable timeframes after life. The second is preferred for spacecraft in Low Earth Orbits (LEO) as they do not require additional systems or significant propellant allocations. The downside is that they pose a risk to the human population when they re-enter.

In order to maintain levels of space debris which are acceptable, requirements are imposed upon spacecraft which require that they are reentered within 25 years or placed into safe orbits if the spacecraft are within specific protected regions. Further to this, a requirement that the casualty risk must be below 10^{-4} is specified. This is avoided for controlled de-orbits where the safety constraints are met by ensuring that the spacecraft (in its fragmented state) impacts safe areas such as the ocean. Controlled re-entry comes with the additional burdens of mass and cost and must be performed whilst the spacecraft is still operational. Uncontrolled re-entry naturally has benefits in terms of being passive and not requiring additional systems, propellant, or to be operational when re-entry occurs. The ability to maintain operability as long as possible is naturally a significant advantage for many space missions.

As was considered and assessed in previous studies, the opening of the outer satellite structure during or prior to re-entry helps to reduce the casualty risk on ground. In order to effectively investigate techniques and technologies to open and/or release external elements, an understanding of the mechanisms at play on these elements during re-entry is needed. In order to achieve this, a review of current relevant joining technologies was carried out to select a number of these for testing. An array of morphological tests was then planned and carried out to characterize these technologies using re-entry simulation chambers.

Following this, development of feasible design concepts to achieve structure break-up or opening at an altitude above the natural break-up altitude was carried out. A selection of these were then developed into breadboard models and tested in order to assess feasibility and effectiveness.

Whilst previous studies focused on a system level overview and the potential impacts of different technologies and techniques for D4D, this study and testing focuses on obtaining results to inform the future selection and implementation of passive technologies, active technologies, and demisable joining technologies.

2 TESTING OF CURRENT JOINING TECHNOLOGIES

The strategy behind the interpretation of the tests is as follows:

- The initial capture of the phenomenology is obtained from the video recordings.
- The common elements and contrasting behaviour in different tests is noted.
- The post-test photographs are examined to confirm the evidence of the behaviour observed in the videos, and to enhance the understanding obtained.
- The phenomenology is the cross-referenced against the thermocouple readings to improve the understanding.
- Finally, this is cross-referenced against the numerical rebuilds in order to build a more complete picture of the behaviour.

Clearly, a complete analysis of all of the test data is a huge undertaking, and presented here is only a top-level analysis and identifies the key points of learning from this test campaign. With this being the most comprehensive set of data on the high temperature failure of structures and joints in re-entry, the first task is to extract the macroscopic phenomenological events in order to ensure that the basics are understood prior to a more complete analysis being performed.

A very important observation is the differences in the failure mechanisms observed when the trajectory heat flux profile is used, relative to the constant flux level. It is worth noting that the trajectory is representative of a shallow uncontrolled re-entry, and that the constant flux is representative of the flux in the expected region of failure. It is clear that the gradual heat soak into the material in the shallow re-entry results in a more isothermal temperature profile than is seen in the constant flux case. This, in turn provides sufficient time for the potting material to denature, which occurs once the activation temperature (about 335^0C) for the epoxy material is reached, resulting in the joint being sufficiently weakened that the insert can be pulled out.

This is observed consistently within the trajectory heat flux tests, and pull out of the insert is not observed in the constant flux tests in either the static re-entry chamber or the wind tunnel. The impact of CFRP facesheets is small on the insert pull-out timing as the lower conductivity is offset by the lower thermal inertia.

The rebuilds of the test data are very good across the vast majority of tests. It is clear that a distinction is required between scenarios where the joints might be expected to fail, and scenarios where the panel might be expected to fail given that both have been observed in the tests. A set of joint failure criteria have been devised, such that triggering these results in joint failure being modelled, otherwise the panel is assumed to have failed.

Application of these models to the re-entry case used to derive the test conditions shows that the spacecraft is expected to heat up significantly before the forces become large, and that this occurs at altitudes significantly higher than the ‘standard’ 78km used in many models. The most likely source of force to promote separation is thought to be centrifugal, with spin rates of 90 degrees per second easily sufficient to promote insert pull-out. Therefore, these tests suggest that the joint failures of standard joints would occur in the 85km-90km altitude range.

3 TESTING OF DEMISABLE JOINING TECHNOLOGY OPTIONS

Of the 4 technology types tested, some clear results could be drawn regarding the effectiveness and applicability for future D4DBB purposes.

The composite inserts showed no gains in demise and clearly can not be adopted for D4D usage without significant changes in terms of construction and materials.

The bonded cleats provide a slight increase in demise performance but in the context of improving the demise of the spacecraft, it is clear that significantly high altitudes are required in order to improve the overall demise. The bonded cleats remain highly ranked as when considered to be applied as within the testing where one side is bonded and the other bolted, they provide system benefits and are a low cost solution. When one side is mounted so that it is external, this brings clear benefits in demisability but also has strong drawbacks in terms of application.

The 2 part demisable inserts and the SMA cylinders for bolt fracture are the clear leaders when it comes to release of panels and increase in spacecraft demisability.

Regarding the current status of the technology, the SMA’s have a higher TRL when considered in their current configuration but have high system impact. This can be mitigated to some extent by modifying the application of the technology and embedding it within the functionality of one of the other parts such as the cleat or the insert itself. The SMA has the very clear benefit of introducing force to assist in panel release. The materials are also tuneable so that if a large scale test or production was to occur, they can be tuned so that the activation temperature is at the limit thus providing the maximum possible break-up altitude with some minor development.

The 2 part demisable inserts come with the benefit that they are a simple replacement of the current insert technology. They do not store any energy themselves but due to their melt process do provide the chance for the low forces present to separate the panels. Their low system impacts and complexity are clear benefits of further adoption of this technology.

It is clear that when considering a whole satellite that not one single technology is likely to be the correct path forward but rather to adopt technologies as they best suit to the applications. For future studies and missions, indeed demisable joining technologies would need to be implemented across the spacecraft and potentially for internal joining technologies in order to ensure early and significant demise of the spacecraft.

4 CONCLUSIONS

The D4DBB study has catapulted the understanding of demise greatly ahead. The technologies currently used and how they react to re-entry conditions has been explored with significant gains in understanding and the potential evaluation of demise effects. The limits of the previous understanding have been explored, gaining valuable knowledge of the representativeness of our analysis tools and highlighting a number of fronts in which assessments can be improved in the future.

A number of technologies were explored to different depths and the most promising of those in terms of future usage and knowledge to be gained were tested in a similar way to current joining technologies. This has also expanded the understanding of the implementation and applicability of technologies for demise across satellites and how this can be handled going into the future.