Chapter 21
Assessing the Resiliency of Composite Structural Systems and Materials Used in Earth-Orbiting Spacecraft to Hypervelocity Projectile Impact

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Abstract Spacecraft that are launched to operate in Earth orbit are susceptible to impacts by meteoroids and pieces of orbital debris (MOD). The effect of a MOD particle impact on a spacecraft depends on where the impact occurs, the size, composition, and speed of the impacting object, the function of the impacted system. In order to perform a risk analysis for a particular spacecraft under a specific mission profile, it is important to know whether or not the impacting particle (or its remnants) will exit the rear of an impacted spacecraft wall. A variety of different ballistic limit equations (BLEs) have been developed for many different types of structural wall configurations. BLEs can be used to optimize the design of spacecraft wall parameters so that the resulting configuration is able to withstand the anticipated variety of on-orbit high-speed impact scenarios. While the level of effort exerted in studying the response of metallic multi-wall systems to high speed particle impact is quite substantial, the extent of the effort to study composite material and composite structural systems under similar impact conditions has been much more limited. This paper presents an overview of the activities performed to assess the resiliency of composite structures and materials under high speed projectile impact. The activities reviewed will be those that have been aimed at increasing the level of protection afforded to spacecraft operating in the MOD environment, and more specifically, on those activities performed to mitigate the mechanical and structural effects of an MOD impact.

21.1 Introduction

Spacecraft that are launched to operate in Earth orbit are susceptible to impacts by meteoroids and pieces of orbital debris (MOD). These impacts can occur at ex-

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tremely high speeds and can damage flight- and mission-critical systems. As a result, spacecraft designers must be aware of the response of various spacecraft components and structural elements under high speed impact loading conditions. Precautions must be taken to ensure that a spacecraft's operation and functional units are not compromised when it is (inevitably) struck by an orbital debris particle or by a meteoroid.

Of course, the effect of a MOD particle impact on a spacecraft depends on where the impact occurs, the size, composition, and speed of the impacting object, the function of the impacted system, etc. The result of such an impact can be minimal (a small hole or crater on a remote non-functional spacecraft surface), or it can degrade a functional spacecraft component (overlapping pits on a mirror or telescope lens), or it can compromise spacecraft functionality, even to the point of loss of life (a perforated ISS module).

The traditional approach to mitigating damage that would be caused by such impacts consists of placing one or more 'bumper' shields small distances away from the primary load-bearing 'inner wall' of the spacecraft. Behind the inner wall of such a multi-wall system, as in the case of the International Space Station, for example, are located the equipment racks, crew quarters, science experiment hardware, etc. This concept was first proposed in 1947 as a means of mitigating the potentially hazardous effects of meteoroids and, within the last three decades, orbital debris. This 'bumper' derives its effectiveness by shattering the projectile and converting it from a discrete concentrated mass to a wide-angle spray of much smaller particles, some of which could even be in a molten or gaseous state.

However, most satellites launched into Earth orbit, and even some manned spacecraft (such as the Space Shuttle), are constructed with honeycomb sandwich panels as their primary structural load bearing elements without a bumper shield because design, cost, and / or mission constraints prevent the inclusion of a protective shield. In these cases, the load-bearing honeycomb sandwich panels (HC/SPs) also serve as the protection systems for the spacecraft components that are located behind them, such as electronics, avionics, fuel cells, pressure vessels, etc.

In order to perform a risk analysis for a particular spacecraft under a specific mission profile, it is important to know whether or not the impacting particle (or its remnants) will exit the rear of a spacecraft wall system, whether it is a 'Whipple-type' multi-wall system or a 'single' HC/SP wall. This issue, that is, whether or not the ballistic limit of a spacecraft wall system will be exceeded under a given set of impact conditions, has been studied extensively over the last five decades by many investigators. A variety of different ballistic limit equations (BLEs) have been developed for many different types of structural wall configurations. For an overview of the various efforts performed in the areas of BLE development spacecraft protection against damage caused by MOD impacts from the late 1950s through the early 2000s, the reader is referred to [1].

In general, BLEs define the threshold particle size that will cause perforation of the rear wall of a structural wall system as a function of variables known to affect the ballistic limit, namely, impact velocity and angle, particle density and shape, and component wall thicknesses and material properties. These ballistic limit equations are typically drawn as ballistic limit curves (BLCs) that are lines of demarcation between regions of rear-wall perforation and no perforation for a given spacecraft wall system under consideration. Once developed, BLEs and BLCs can be used to optimize the design of spacecraft wall parameters so that the resulting configuration is able to withstand the anticipated variety of on-orbit high-speed impact scenarios. By understanding the debris environment size and velocity distributions that are expected to impact a spacecraft, spacecraft shielding and designs, as well as their associated BLEs, can also be tailored to meet spacecraft risk requirements while minimizing weights.

NASA and ESA continue to develop BLEs for their structural configurations of interest. The majority of the NASA and early ESA efforts have been directed towards developing BLEs for dual-wall systems such as those that can be found on the International Space Station. The high-speed impact testing that provided the data for these BLEs typically used spherical aluminum projectiles fired in light gas guns at impact velocities between 3 and 7 km/s. This data was fitted with scaled single-wall equations below 3 km/s, and with theoretical momentum-based or energy-based penetration relationships above 7 km/s to obtain three-part BLEs that cover the full impact velocity range of interest, that is, from approx. 0.5 to 16 km/s. It is important to note that the empirical nature of these BLEs subjects them to potential inaccuracy, particularly when applied to spacecraft wall configurations that have not been well tested.

NASA has encoded their BLEs in Bumper II, the software application tool it uses to perform MOD risk assessments. The original Bumper tool was developed in the mid-1980s for the Space Station Freedom Program. Bumper was upgraded to Bumper II in 1991, and separate versions of Bumper II are used now for Space Shuttle, Space Station, Constellation Program risk assessments. Reference [2] presents an overview of the development of Bumper II, including the underlying advances in high-speed impact response prediction for multi-wall structures from the mid-1960s through the mid-2000s.

Similarly, the BLEs developed by ESA reside in that agency's risk assessment tool ESABASE. Like Bumper II, it is a 3-D numerical analysis tool for evaluation of MOD environments, impact probabilities and resulting damage effects. It is based on the latest MOD environment models and particle/wall interaction models, and provides impact probabilities and resulting damage effects for user specified spacecraft geometry and mission parameters. ESABASE, as does Bumper II, merges MOD environments, failure criteria, and damage predictions to produce risk estimates for specified levels of crew, mission, or vehicle loss.

21.2 Historical Overview

A review of the literature reveals that while the level of effort exerted in studying the response of metallic (mostly aluminum) multi-wall systems to high speed particle impact is quite substantial, the extent of the effort to study composite material and composite structural systems such as HC/SP panels under similar impact conditions has been much more limited. The two main information sources for this subject are the proceedings of the International Ballistics Symposia (published by the host organization) and the proceedings of the Hypervelocity Impact Symposia (published by the International Journal of Impact Engineering). An overview of the papers presented at these venues on the subject of high speed impact of composite materials and HC/SPs is shown in Fig. 21.1. Also shown in Fig. 21.1 is an accounting of papers on this topic appearing in other venues and journals. As can be seen in Fig. 21.1, interest in this area of research is rapidly increasing, especially since the 1990s.

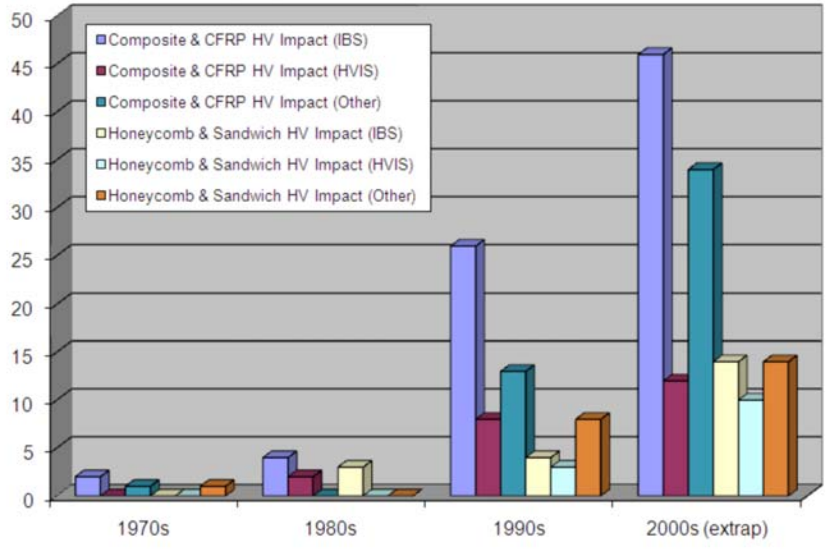

Fig. 21.1 Number of Papers on Composite and HC/SP HVI.

The objective of this paper is to present an overview of the activities performed by the scientific and engineering communities to assess the resiliency of composite structures and materials under high speed impact. Specifically, in this paper we focus on composite materials subjected to hypervelocity impact, that is, impact speeds on the order of 2 km/s and higher. This study of composite materials under these loading conditions is a relatively new field of scientific and engineering study, as opposed to the study of composite materials under low velocity impact. There is also a phenomenological demarcation between impact regimes. At ’hypervelocity’, the impacting materials behave, for all practical purposes, as fluids. That is, material densities, equations of state, and the principles of shock physics govern the impact and recovery processes; considerations of material strength, elasticity, and even plasticity are second-order effects, and enter the response analysis primarily in the later stages of such impact events. At ’low velocity’ the opposite is true: response is governed primarily by material strength considerations.

The activities reviewed in this paper are those that have been aimed at understanding and increasing the level of protection afforded by such systems to satellites and spacecraft operating in the MOD environment, and more specifically, on those activities performed to mitigate the mechanical and structural effects of an MOD impact. These effects include primarily the penetration and perforation of spacecraft systems and subsystems. Since the results and papers presented at the IBS typically deal with ordnance-type impacts involving armor/anti-armor engagements, the subject matter of these papers, as well as others concerned with ordnance-type impacts, is outside of the scope of the current review activity.

21.3 Composite Material Panels

21.3.1 HVI Response Characterization

Early studies performed in the 1960s, 1970s, and 1980s stemmed from the realization that earth-orbiting spacecraft and their components are exposed to ultra-high speed impacts by meteoroids; orbital debris was not yet considered a problem (see, e.g., [3]-[6]). Serious attention began to be paid to the problem of very high speed impact of composite materials in the 1980s (see, e.g., [7, 8]) for a number of reasons.

- Manufacturing costs became more reasonable and construction protocols more standard. This allowed composite materials to be considered for use in an increasing number of spacecraft applications. Space station trusses [9], robotic arms and booms [10, 11], fuel tanks and pressure vessels [12] were all designed to be to be made from some form of composite material.
- Orbital debris rose to the forefront as perhaps the most serious spacecraft design consideration. Since the average impact velocity of a debris particle was as much as a factor of 5 lower than that of a meteoroid, it was thought that the high

strength of composite materials might be able to play a larger role in lowering the damage potential of on-orbit impacts by orbital debris particles.

- LDEF post-retrieval symposia also provided many opportunities for scientists and engineers to comment on impact damage morphologies in the composite material portions of the retrieved satellite (see, e.g., [13]-[16]).

Most of the early HVI studies were performed to characterize the tendency of an impacted composite material panel to degrade through delaminations within the laminate at locations not readily apparent through visual inspection. This characteristic of composite materials makes repairing whatever damage might have occurred exceedingly difficult, which is in stark contrast to our ability to see and repair damage to metallic panels. For example, a simple cratering event in a composite material panel will also cause delaminations to occur over distances many times the crater diameter away from the impact site. However, whatever crater damage is observed in a metallic panel constitutes all or nearly all of the damage sustained by the panel; whatever additional internal damage may exist is minimal and is in the immediate vicinity of the original crater itself. It was, therefore, very important to characterize this damage propagation characteristic of composite materials [17]-[21]. Residual strength of impact composite material panels was concern [22], as was the synergism between HVI damage and atomic oxygen erosion [23].

Some studies also tried to see if mathematical models currently used to approximate the HVI response of metals could also be applied (and if so, with what level of accuracy) in the modeling of the response of composite materials to HVI loadings. Yew and Kendrick [8], Sil'vestrov [24] and Homae [25] found that they could, for example, if the impacted composite plates were 'relatively thick' and if the response characteristic of interest was a 'global' quantity like a hole diameter or a penetration depth. More recently sophisticated numerical and analytical modeling techniques have been developed (see, e.g., [26]-[29]) that have allowed HVI loadings of composite materials to be analyzed by hydrocodes such as Autodyn.

Other response characterization studies were aimed at suggesting improvements in laminate construction (e.g. braiding as opposed to filament winding [30] that would increase those materials' resistance HVI damage. One positive response characteristic that was noted early on was that composite materials produce much less impact ejecta than did metals under the same impact conditions. Furthermore, whatever ejecta are produced by an HVI on a composite material is much less dense than the corresponding metallic ejecta [31]. These properties are important in space applications where there is a desire to not only not pollute further the orbital environment with more solid particulates, but also to not create particles that can strike other exposed spacecraft components as they are ejected from the impact site. Of course, composite material configurations are getting more and more sophisticated – several recent studies have explore the HVI of CFRP sandwiched in between two layers of Kevlar [32, 33].

21.3.2 Use in MOD Protection Systems

As is the HVI response characteristics of composite materials began to be established, attention quickly turned to their use as part of perforation resistant structural systems on the international space station. Work in this area proceeded fairly sequentially, with first consideration being given to using composite materials as outer bumpers in dual-wall systems, then as inner bumpers in multi-wall systems, and then finally as the innermost walls in multi-wall systems. The following sections discuss some of the highlights of the work performed by the HVI community in assessing the effectiveness of composite materials as part of a perforation-resistant structural wall system.

Composite Outer Bumpers

The response of dual-wall systems with Kevlar and graphite/epoxy (Gr/Ep) outer bumpers was compared against that of equal-weight all-aluminum dual-wall systems in the late 1980s by Schonberg [34]. The aluminum bumpers were more effective in spreading out the debris created by the initial impact on the bumper than were the Kevlar bumpers. Apparently the interaction of the shock waves in the projectile and the Kevlar bumpers prevented complete break-up of the projectiles, which decreased the dispersion of debris cloud fragments, thereby increasing the likelihood of pressure wall perforation. However, the pressure wall damage areas in dual-wall systems with Gr/Ep bumpers more wide-spread than those in equivalent systems with Kevlar bumpers. Pressure wall perforations in Gr/Ep systems consisted of several small holes, not one large hole as in the Kevlar systems. From these results, it was concluded that using a laminated composite as the outer bumper in a dual-wall system does not offer any protection advantage as compared to the protection level provided by an all-aluminum dual-wall system.

These results were supported by Christiansen [9], who performed an in-depth study in the early 1980s to evaluate the effectiveness of metallic, composite, and ceramic materials as MOD shields. Christiansen found that while Gr/Ep alone did not shield as well as did aluminum, it had some potential to enhance MOD protection levels when used as the second bumper in a double-bumper system with an aluminum outer bumper. The use of composite materials as inner bumpers is discussed in the next section.

The 1990s saw an increase in the number of studies performed using composite materials (either CFRP or metal-matrix) and/or ceramic materials as outer bumpers in dual-and multi-wall systems. Porous fillers as part of all-aluminum multi-wall systems were also considered [35, 36]. In nearly all of the studies, the results showed that the composite material bumpers faired at best only marginally better in terms of ballistic limit of the dual-wall systems than their equivalent monolith aluminum counterparts (see, e.g. [37]-[40]). However, there were some differences in bumper hole sizes, fragmentation of the impacting projectile, debris cloud composition and motion/spread between the dual-wall systems with composite and with aluminum bumpers.

Composite Inner Bumpers

The response of triple-wall systems with Kevlar and Spectra inner bumpers was compared against that of all-metallic triple-wall systems [41]. In nearly all the Kevlar inner bumper tests the Kevlar panels were not perforated, whereas their aluminum counterparts sustained large holes. In the Spectra tests, both the Spectra and aluminum inner bumpers were perforated. However, the pressure walls in the Spectra systems sustained little or no damage, while those in corresponding all-aluminum systems were usually perforated. These results demonstrate that using a composite material as the inner bumper does increase the protection afforded to a spacecraft against damage caused by MOD impacts. In a recent study, Katz [42] developed an analytical model to study the energy absorption mechanisms that come into play when composiste materials such as those considered by Schonberg in [41] are struck by projectiles travelling at hypervelocities.

Other multi-wall shielding concepts involving composite materials as the inner bumper(s) that have been tested under HVI loading conditions were a Nextel multi-shock shield [43]-[46], a mesh double-bumper shield [44, 47, 48], a hybrid Nextel/aluminum multi-shock shield [49], a double-bumper shield using with a GLARE inner bumper [50], an all-mesh multi-bumper shield [51], and a so-called ’stuffed Whipple shield’ in which a layer of Kevlar and Nextel cloth blankets is placed between the bumper and pressure wall of a traditional all-aluminum Whipple-type system [52, 53].

As summarized by Schonberg in [1], the results of the various test programs performed showed that multi-wall systems involving composite material bumpers, especially those made of Nextel as in the stuffed Whipple shield, in combination with aluminum bumpers produced less damaging secondary debris or ejecta, were

- more efficient in converting the projectile’s kinetic energy into internal thermal energy,
- less sensitive to projectile shape,
- less sensitive to the obliquity of the impacting projectile,

and resulted in less cumulative damage to the pressure wall of the multi-wall system when compared with traditional Whipple-type all-aluminum single-bumper systems (see also [54]). In addition, such multi-wall systems were found to provide better protection against more hazardous non-spherical projectiles when compared to the protection level offered by all-aluminum systems [55].

Regarding the performance of the stuffed Whipple shield, while the test results in Ref. [52] showed that such a system provides a large increase in the ballistic limit over corresponding unenhanced systems, test results obtained in the late 1990s have shown that a perforation of a stuffed shield system, if it occurs, could be catastrophic from a cracking standpoint [56]. As such, the marked increase in ballistic limit that comes from using a Nextel/Kevlar blanket instead of the more traditional MLI blanket must be balanced in a risk assessment calculation with possible increases in crew vulnerability as a result of increased post-perforation air leak rates [57, 58]. Initial results indicate that when all catastrophic failure modes are considered, catastrophic loss appears to possibly be more likely for weaker shields than for the more robust stuffed Whipple shield.

Composite Pressure Walls

In the mid-1990s, a study was performed to compare the response of dual-wall systems with Gr/Ep pressure walls against that of equal-weight all-aluminum dual-wall systems [59]. The results showed there are several advantages of using Gr/Ep as a pressure wall material: (1) it eliminates severe cracking and petalling sustained by aluminum walls in systems impacted by large projectiles; (2) its ballistic performance is superior to that of aluminum for impact velocities above 5.5 km/s; and (3) patching a hole in a perforated Gr/Ep panel, even if it were larger than in an aluminum panel, would be relatively easy since the Gr/Ep remains non-deformed and the patch can be, e.g., adhesively bonded. Repairing a perforated aluminum wall would be a more difficult procedure since the aluminum would likely be cracked and petalled. On-orbit repair of perforated aluminum panels would therefore require cutting and welding tools that are EVA compatible, while the repair of perforated Gr/Ep panels would not.

In a recent numerical study, Ito and Sekine [60] found that the ballistic limit of a dual-wall system with an aluminum bumper and a Gr/Ep pressure wall can be increased if a thin aluminum plate were to be bonded on the 'top' surface of the Gr/EP pressure wall. However, despite their apparent potential for use as the innermost wall in perforation resistant structures, it appears that other issues, such ease of construction and manufacturability, continue to prevent composite materials from being considered for and used in this capacity.

21.4 Honeycomb Sandwich Panels

Most satellites launched into Earth orbit are constructed with honeycomb sandwich panels (HC/SPs) as their primary structural load bearing elements. A typical honeycomb sandwich panel is shown in Figure 21.2.

Fig. 21.2 Generic Honeycomb Sandwich Panel with Aluminum Facesheets.

Behind such panels are located spacecraft components that are appropriate for the particular spacecraft or satellite mission and function (e.g. electronics, avionics, fuel cells, pressure vessels, etc.). In order to be able to perform a risk analysis for a particular satellite under a specific mission profile, it is important to know more than just whether or not the satellite will be struck by a meteoroid or an orbital debris (MOD) particle. It is equally important to know, in the event of such an impact, whether or not the impacting particle (or its remnants) will exit the rear of the HC/SP (i.e. whether or not the ballistic limit of the HC/SP will be exceeded) and, if so, where the debris created in such an impact will land and what internal components it will strike. In this section, we discuss the work that has been performed by various researchers in the hypervelocity impact community to address these two issues.

21.4.1 Early Work – The 1960s and 70s

Perhaps the first study performed involving HC/SPs being struck by very high speed projectiles examined the effectiveness of aluminum honeycomb shields in preventing meteoroid damage to liquid-filled spacecraft tanks [61]. Much like the monolithic shields proposed by Whipple, HC shields were found to shatter impacting projectiles and scatter impact debris over a wide area of the protected tanks. The spacing between the HC material and the tank was found to have a significant effect on the damage levels sustained by the tanks. This led the authors to conclude that the effectiveness of the HC shield material to protect against meteoroid impact was inconclusive. This uncertainty in the effectiveness of HC shields was reinforced by a subsequent study that explored the channeling effect associated with impacts on HC/SPs [62]. By subjecting a HC/SP mock-up to high speed impacts, this study concluded that ’[do] indeed have the ability to channel debris against the second sheet’ in a multi-wall configuration. Following these two studies, interest in using HC/SPs as meteoroid shields for spacecraft being developed and flown in the 1960s, 70s, and 80s understandably declined.

In an effort to study the channel effect noted by early investigations, Jex, Miller, and McKay subjected dual-wall systems without and without HC filler to high speed impact [63]. Much to everyone’s surprise, they found that ’the HC structure had a better predictive capability that the same structure without honeycomb when ballistic limits were compared.’ They suggested the reason for this was that the secondary fragmentation and energy loss associated with the initial impact debris fragments hitting HC walls as that debris travelled through the HC more than overcompensated for any channeling effects. However, by the time the results of this study were made, monolithic shielding had already become the preferred configuration for protecting spacecraft against meteoroid impacts.

21.4.2 The 1980s and 90s

High speed impact testing of HCSPs experienced a rebirth in the late 1980s and early 1990s when an increasing number of satellites were being designed with HCSPs as the main load-bearing structural elements and subsequently subjected to potential impacts by man-made debris in earth orbit. The question naturally arose as to how well these satellites would fare if such an impact were to occur. In an early study that attempted to answer this question for the (then) newly developed RADARSAT [64], it was found that yes indeed an orbital debris particle impact on certain critical satellite components would bring the survivability down to an unacceptably low level. As a result of the results obtained, ’[a] number of modifications considered practical in terms of weight, volume, and cost were implemented to improve protection of the more critical units.’ In another satellite impact study, the results of eighteen (18) tests that were performed (1) to determine the ballistic limits of typical AXAF HC/SPs, and (2) to quantify the extent of damage to underlying AXAF components in the event of an HC/SP perforation are presented and discussed in a fair amount of detail [65, 66].

HC/SPs were also considered briefly as possible bumpers in early space station wall impact studies (see, e.g., [67]). However, the thrust of this particular study, for example, was not so much the HC/SPs or their protected systems, but rather the exterior space station components in the vicinity of an impact that could be affected by ricocheting secondary debris. No significant difference between the ricochet particle generation ability of HC/SPs and that of monolithic bumpers was noted by the authors.

Other spacecraft components either protected by or made with HC/SPs that were tested under hypervelocity loading conditions include Ni-H battery cells [68] and metallic thermal protection systems [69]. The tests involving Ni-H batteries showed that for all of the test conditions investigated, the battery cells responded ’in a benign manner ... [they] simply vented their hydrogen gas and some electrolyte following a perforation, but did not burst or generate any large debris fragments.’ The authors found that while a ’hypervelocity impact on a Ni/H2 cell used in space would result in the loss of functionality of the battery of which it was part of [sic], but would not result in a catastrophic failure that would cascade to other cells or nearby hardware.’ Unfortunately, with respect to the metallic TPS study, although the paper discusses the results of some high speed impact tests performed in support of the development of a ’superalloy honeycomb TPS concept’ for the Reusable Launch Vehicle, those results are not actually presented. Hence, it is difficult to assess the validity of the claims made regarding such a TPS construction as being an ’attractive, viable candidate for the RLV.’

Towards the end of the 1990s, a series of studies was performed in Europe to ’determine ways to improve the tolerance of unmanned spacecraft to hypervelocity impacts by the use of shielding with minimal additional cost, mass and volume,’ and, by assessing the orbital debris and meteoroid threat for two (then) new satellites, METOP and ERS-2, ’demonstrate the benefits of [that] new shielding.’ [70]-[78] The work performed considered single as well as double-layer HC/SPs, and the use of multi-layer insulation blankets, either on its own or with a HC/SP. The studies concluded that double-layer honeycomb shielding, combined with a secondary shielding of internal components, wiring, etc, is a cost- and mass-effective way in which to enhance the robustness of a spacecraft operating in the meteoroid and orbital debris environment.

The studies performed to develop cost-effective debris shields also compared the response of dual-wall systems with HC panels against that of similar monolithic all-aluminum systems. They found that because of its internal construction, an impacted HC panel is able to absorb a significant portion of the energy associated with the debris created by the original impact. As such, spacecraft protected by HC panels would be expected to fare better in the M/OD environment from a protection perspective than would comparable all-aluminum systems. These conclusions were confirmed by other investigators as well (see, e.g., [79, 80]).

21.4.3 Recent Work

Testing in support of the METOP and ERS-2 study was performed at the Fraunhofer Ernst-Mach-Institute, where work was also underway to understand the response of other typical satellite and/or spacecraft wall systems: Rosetta, EnviSat, GOCE, BeppoSax, RADARSAT2, and the ATV [81]-[90]. These studies again confirmed that 'sandwich panels have a better tolerance to hypervelocity impacts than monolithic structures,' and that placing a blanket of MLI 'in front of the sandwich panels contributes significantly to the overall protection performance' of those panels. Detailed numerical models of HC/SPs have also recently been developed to support the tests being performed [91]. Information gleaned from numerical analyses of HC/SPs under hypervelocity impact provides additional insights into the response of such structures, and can be used to tailor a particular HC/SP design to enhance its impact performance.

Most recently, over one hundred impact tests were performed at Fraunhofer EMI to assess the vulnerability of a variety of representative spacecraft components (e.g. fuel pipes, heat pipes, pressure vessels, electronics boxes, harnesses, and batteries) to simulated MOD impacts [92]-[94]. Post-impact functionality of these components was studied and compared and against required minimums. In the end, the authors were able to provide recommendations for general spacecraft design considerations with regard to the elements they test as well as an assessment of the consequences on spacecraft operation of various possible damage levels. In addition, the study showed that the particle diameters that would lead to equipment or component failure are several times those required to perforate the structural walls of the spacecraft only.

Another outcome of the spacecraft component vulnerability study was a new BLE that could be applied to various structural configurations, including single wall systems, dual-wall systems, multi-wall systems with HC/SPs, batteries, e-boxes, harnesses, etc. [95, 96]. To assess how well these BLEs performed in terms of predicting perforation (P) or non-perforation (NP) of HC/SP systems with aluminum and composite facesheets, an exercise was undertaken to compare the P / NP predictions of the equations in [95] and in [96] against actual P/NP occurrences as found in the data from the experimental investigations discussed in this section [97]. It was found that these BLEs are fairly conservative: they successfully predicted HC/SP perforation in nearly all of the tests that resulted in perforation, while allowing approximately half of the non-perforating tests to be incorrectly labeled as tests with a perforation. This indicates the likelihood that use of these BLEs in design applications could result in overly robust shielding hardware. The reader is also referred to Reference [98] for additional details regarding the work performed on numerical simulation of HC/SPs under MOD impact loads.

In addition to knowing whether or not the impacting particle (or its remnants) will exit the rear of the HC/SP, it is equally important to know, if indeed the ballistic limit of the HC/SP has been exceeded, where the debris created in such an impact will land and what internal components it will strike. To help address this issue, a system of empirical equations that can be used to predict the trajectories and spread of the debris clouds that exit the rear facesheet following a high speed perforating impact of a HC/SP was recently developed [99]. The equations developed in this study incorporate the following features:

- presence (or the lack thereof) and composition of a multi-layer thermal insulation (MLI) blanket on the exterior of the HC/SP;
- material composition of the HC/SP facesheets (either aluminum or a carbon-fiber-reinforced polymer, or CFRP);
- facesheet thicknesses and overall HC/SP thickness;
- HC core properties (core size, wall thickness, and material); and,
- projectile diameter, material, impact velocity, and trajectory obliquity.

Empirical equations were also developed to predict the dimensions of the holes in the front and rear HC/SP facesheets. These hole dimension equations can be used to calculate the amount of mass in a debris cloud if the HC/SP is perforated by a high speed impact. The trajectory angles can then be used to determine where this mass will travel and what spacecraft components will be impacted, and the spread angles equations will determine the extent of the footprint made by this mass on any encountered surface. All of this information can then be fed into a risk assessment code to calculate the probability of spacecraft failure under a prescribed set of impact conditions.

21.5 Conclusions

This paper has presented an overview of the work performed by the scientific and engineering communities to assess the resiliency of composite structures and materials under high speed impact. The activities reviewed are those that have been aimed at understanding and increasing the level of protection afforded by such systems to satellites and spacecraft operating in the MOD environment, and more specifically, on those activities performed to mitigate the potentially deleterious mechanical and structural effects of an MOD impact. It was found that

- using a laminated composite as the outer bumper in a dual-wall system does not offer any protection advantage as compared to the protection level provided by an all-aluminum dual-wall system;
- using a composite material as the inner bumper does increase the protection afforded to a spacecraft against damage caused by MOD impacts; and,
- there are several advantages of using a laminate composite as the pressure or innermost wall material of a multi-wall system, including the elimination of the

severe cracking and petaling that would be sustained by aluminum walls in systems impacted by large projectiles.

The study of HC/SPs under HVI loadings is an on-going research area, with most of the activities focusing on determining whether or not, in the event of a very high speed impact, the impacting particle (or its remnants) will exit the rear of the HC/SP (i.e. whether or not the ballistic limit of the HC/SP will be exceeded) and, if so, where the debris created in such an impact will land and what internal components it will strike. The development of numerical models that simulate such impacts on HC/SPs with increased fidelity is providing scientists and engineers much-needed information that can ultimately be used to develop resilient satellites and spacecraft systems.

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