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Multi-layer insulation material models suitable for hypervelocity impact simulations

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A B S T R A C T

MLI (multi-layer insulation) is present in many spacecraft missions and typically consists of multiple layers of aluminized Kapton separated by fine gauze. It has been observed, depending on the type and position within the structure, that MLI can influence the ballistic performance of panels under hypervelocity impact (HVI) despite being extremely lightweight. Due to the very thin nature of the foils, <10 μm, it is often considered too computationally expensive to explicitly include such materials in HVI simulations of typical structures used in space. Accurate resolution of the foils would require a prohibitive number of elements. This paper reports on the development of a discrete modelling approach that efficiently facilitates the inclusion of such materials and allows for each layer of the MLI to be explicitly represented in the numerical model. Mesomechanical simulations of planar plate impact experiments (PPI) and an HVI event on MLI are presented where each layer of the MLI is explicitly represented with a number of elements through the thickness. The results of these models are then compared with the developed discrete approach suitable for including in larger scale simulations of impacts on real space structures. The current study applies previously developed material models to structural materials such as Carbon Fiber Reinforced Plastics (CFRP). This paper further describes simulation of an HVI event on a CFRP-Aluminum/honeycomb structure at oblique incidence, thereby illustrating that the developed approach for modelling MLI provides a practical method for the inclusion of such materials in full-scale simulations.

1. Introduction

MLI is often used to optimize the thermal environment of a spacecraft and is typically composed of multiple layers of aluminized Kapton separated by fine gauze. The total thickness of which may vary from 2 to 3 mm depending upon the mission specifications. It has also been observed that the presence of MLI can influence the ballistic performance of such a spacecraft structure when exposed to micrometeoroids and orbital debris (MMOD); see, e.g., Refs. [1–5].

It is not feasible, using either continuum volume elements or SPH (smooth particle hydrodynamics) particles, to explicitly represent each individual component of MLI in finite element simulations in models of typical space structures; such as CFRP-Al/HC in which MLI is present. The primary reason for this is the thickness of the Kapton layers, <10 μm. Accurate modelling of such materials would require an unmanageable number of extremely small elements, which in turn requires many computational cycles to be performed due to a reduced time increment between cycles. Consequently, other studies [1,9] have represented the entire thickness of the MLI using a single element of equivalent areal density Kapton or equivalent aluminum. In the work reported here, different simulation approaches were investigated and developed to facilitate the practical modelling of MLI in simulations of representative space structures.

Mesomechanical simulations of PPI experiments and an HVI event on MLI are reported. In these numerical models the individual Kapton layers are explicitly resolved with a suitable number of either SPH particles or continuum elements through the thickness of each individual layer. These simulations provide a better understanding of the dynamic behaviour of the MLI and provide a basis for evaluating the coarser, discrete, modelling approach. The results of these models are then compared with the developed discrete approach for MLI that is suitable for including in larger scale simulations of impacts on real space structures.

Previous studies [6,7] have focused on the development of orthotropic material models suitable for the prediction of impact damage in composite materials used in shielding materials. The current study applies these material models to structural materials such as CFRP. The development of the material data used here is

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given in Ref. [8]. This paper further describes the inclusion of MLI in a simulation of an HVI event on a CFRP-Al/HC structure at oblique incidence, illustrating that the developed discrete approach to modelling MLI facilitates the explicit modelling of such thin materials in simulations of real spacecraft structures.

2. MLI modelling

As part of the work reported here and in Ref. [8], a review of a number of space missions was performed and the typical materials and geometries analyzed. This data provided information such that representative materials could be chosen for the current study to ensure relevance to space structures. The configuration of the MLI selected for this work is given in Fig. 1.

2.1. Planar plate impact tests

2.1.1. Experimental

PPI experiments were performed to obtain a validation basis for the discrete modelling approach to be described below. It was not intended to derive any continuum data for the MLI from these tests – if this is at all possible. Prior to commencing this test campaign some preliminary PPI tests were conducted to verify the feasibility of this test type. There were uncertainties because of the extremely thin-layered structure having to be loaded at velocities of several hundred meters per second. These tests were successful (see Fig. 2), which illustrates the velocity signal of two preliminary tests with and without MLI (the Betacloth layer was present in these tests and oriented such that the Betacloth was impacted first). Although these preliminary tests were not used in the development of the simulation approach it is instructive to understand the difference in these tests with and without MLI present.

The signal jump with MLI present is not as steep as without. This corresponds to shock attenuation within the aluminum target when it is covered with MLI. With MLI present an oscillation of the velocity trace is present. This can be explained by the MLI acting as a gap between the two aluminum plates. The waves travelling within the target are totally reflected on the MLI side, resulting in the 'ringing'-like structure, that can also be observed in spallation experiments. For the MLI test campaign, the Betacloth was removed from the MLI. The orientation of the remaining layers was chosen in such a way that the thin Kapton layer always impacted (when part of the projectile) or was impacted (when part of the target) first. The MLI PPI tests conducted are listed in Table 1 and the results shown in Figs. 3 and 4. The MLI was destroyed completely in all tests.

For the low impedance tests, the free surface velocity level increases with increasing impact velocity, as shown in Fig. 3. In all cases, the Hugoniot elastic limit of the aluminum can be detected as

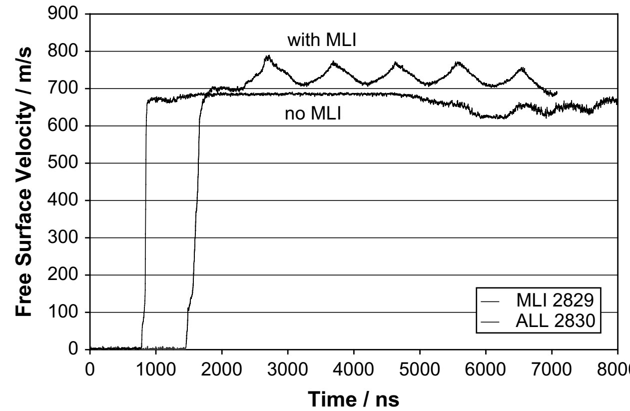

Fig. 2. Preliminary MLI PPI test results. The impact conditions were: 8 mm Al → (0.7 mm MLI) + 3 mm Al. In the case of 'no MLI' an Al-projectile impacts on an Al target. In the other test, the target was covered with MLI on the impacted side.

a small jump in the curves below 200 m/s. The oscillation occurs in all experiments, getting more pronounced with higher impact velocities. The initial peak in each test arises from the impact of the first MLI layer on the target as illustrated in the right-hand graph of Fig. 3. It is most distinctive in test 2895 (at ~250 ns). After this first impact, the MLI structure continues to be compressed and the velocity signal rises at 642 ns. The structure of the signals is different in every test, most likely because on the microscopic scale the MLI layers are never exactly flat and do not impact the target everywhere simultaneously.

The high impedance results of Fig. 4 are shifted in 'time-direction' so that the steep velocity increase occurs always at the same time in the diagram. For test 2894, again an initial peak can be observed; right-hand plot of Fig. 4. In contrast, no such peak can be seen in the direct tests. This is because the MLI is on the target this time and the whole package has to be compressed completely before any momentum can be transferred to the copper plate of the target.

2.1.2. Mesomechanical MLI model

Simulations of the PPI tests described in Section 2.1.1 were run in ANSYS® AUTODYN® using Lagrangian volume elements to represent all parts of the experimental set-up. In all the tests, the 8 mm thick aluminum or copper backing plate was modeled using 1250 Lagrangian elements and 420 elements in the 3 mm target plate.

In these mesomechanical simulations fine resolution of the individual components was required such that five elements could be used through the thickness of each of the MLI layers. Fig. 5 shows

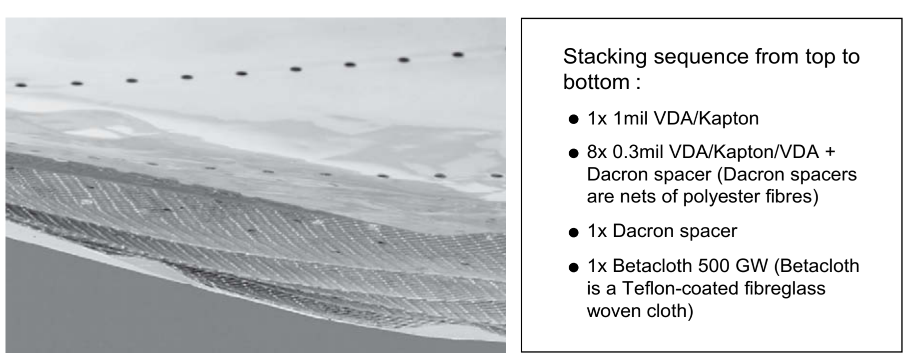

Fig. 1. Configuration of MLI used in the study reported here. The Betacloth and last Dacron spacer shown above were removed prior to testing since this in not representative of a 'typical' MLI configuration. Kapton is a polyimide film; VDA = vapor deposited aluminum.