Statistical Approach on Utilizing Ground-based Experiments to Model Break-up Events

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Abstract

Two laboratory-based impact tests have been conducted to develop and extend the capability of NASA satellite breakup models. The first experiment, the Satellite Orbital Debris Characterization Impact Test (SOCIT), was conducted by the U.S. Department of Defense and NASA in 1992. It employed a fully functional U.S. Navy Transit spacecraft, fabricated from materials commonly used in the 1960s. SOCIT fragmentation data formed the basis of the current NASA Standard Satellite Breakup Model (SSBM). A second experiment, DebriSat, was conducted in 2014 by the DebriSat consortium: the NASA Orbital Debris Program Office, the United States Space Force Space Systems Command, formerly the Air Force Space and Missile Systems Center, the Air Force Arnold Engineering Development Complex, and the University of Florida. This impact test was performed on a high-fidelity mock-up satellite assembled from modern components. Data from both experiments are expected to contribute to the next-generation models for on-orbit breakup analyses, long-term environment predictions, and debris risk assessment.

This paper uses the direct statistical sampling of the SOCIT and DebriSat data ensembles to model an on-orbit breakup event, rather than the analytic expressions estimated from the samples in the SSBM and its predecessor. This direct method involves drawing fragments (*i.e.*, sampling with replacement) from each fragmentation data-subset containing mass, shape category, material density, characteristic length, mass, and cross-sectional area. As part of the sampling process, the properties of sampled fragment data (*e.g.*, area-to-mass ratios) are numerically checked to ensure they do not contain unrealistic quantities. The process to simulate a breakup cloud composed of fragments from SOCIT and DebriSat datasets is discussed. The methodology for ensuring that conservation of overall mass of the sampled fragment cloud under this sampling approach is highlighted. Finally, the results are compared with simulated clouds generated from SSBM for specific historical breakup events.

1 Introduction

The Satellite Orbital Debris Characterization Impact Test (SOCIT) was conducted by the U.S. Department of Defense and NASA in 1992. It employed a fully functional U.S. Navy Transit spacecraft, fabricated from materials commonly used in the 1960s. SOCIT fragmentation data formed the basis of the current NASA Standard Satellite Breakup Model (SSBM). A second experiment, DebriSat, was conducted in 2014 by the DebriSat consortium: the NASA Orbital Debris Program Office, the United States Space Force Space Systems Command, formerly the Air Force Space and Missile Systems Center, the Air Force Arnold

Engineering Development Complex, and the University of Florida. This impact test was performed on a high-fidelity mock-up satellite assembled from modern components.

The NASA SSBM provides an average breakup debris cloud for collisions and explosions of spacecraft and upper stages. It was developed from laboratory test results and ground-based remote measurements of on-orbit fragmentation events, following significant validation efforts against observable data. The SSBM was introduced in EVOLVE 4.0 – a predecessor to the LEGEND (LEO-to-GEO Environment Debris) series of long-term debris-environment models – and is described in detail by [1]. The traditional SSBM method uses pseudo-random values (determined by pseudo-random number generation) to sample analytical multivariate distributions that have been fitted to the properties of sample fragment populations, such as fragment size, mass, area, and density. The incorporation of fragment shape as a model parameter is a difficult problem in the context of this prior work, suggesting that new methods and techniques are required.

For this work, a statistical database-sampling method is employed, whereby a laboratory impact fragment dataset ("fragment database") is directly sampled with replacement and the selected fragment properties are adopted for the modeled break-up cloud. A database-sampling approach has two significant advantages operationally over the traditional SSBM approach: (1) the database-sampling approach can be readily updated as more fragments are collected, and (2) the additional fragment parameter – shape – becomes accessible without the need to develop a probabilistic shape model. One limitation is that the database is finite and cannot be projected beyond the sample space, so analytical models must still be used to extrapolate past the sample limits of the database. For a larger cloud where sampling with replacement is needed, it is also necessary to randomly perturb the characteristics of each drawn piece to avoid the presence of identical constituents.

This paper provides the rationale for deciding which fragment databases – SOCIT or DebriSat - to use for simulating a breakup event. The process for sampling fragments from a dataset to model a breakup event is discussed. One catastrophic collision is modeled using this database-sampling approach. Finally, the mass and area-to-mass ratio (A/m) distributions from this model and the SSBM are compared.

2 Materials Category

To select which fragment database will simulate an on-orbit breakup event, the material components of a given parent body must be reviewed. One of three materials category descriptors (Table 1) is assigned to the material constitution for historical payloads and R/Bs. A study of historical launch traffic prior to 2021 concluded that the determining factor between classic and modern composition is the existence of carbon fiber reinforced polymers (CFRP), glass fiber reinforced polymers (GFRP), multi-layer insulation (MLI), and composite structure in the parent body. If all these materials exist in the parent body, then the space object is classified as modern and the DebriSat fragment database is statistically sampled. If none of these materials are present, the space object is classified as classic, and the SOCIT database is sampled. If some of these materials are present, then the object is assigned a mixed materials category and both impact databases are employed.

Table 1. Materials Category Designations of Historic Launch Traffic

Descriptor	Identifying materials	Relevant Database
Classic	***No*** CFRP/GFRP ***or*** MLI ***or*** composite structure	**SOCIT only**
Modern	CFRP/GFRP ***plus*** MLI ***plus*** composite structure	**DebriSat only**
Mixed	***Some*** CFRP/GFRP ***or*** MLI ***or*** composite structure	**Both SOCIT & DebriSat**

A parameter k_{mix} quantifies the decimal fraction of the total mass to be drawn from the classic (SOCIT-based) database, and the remaining 1- k_{mix} is to be drawn from the modern (DebriSat-based) fragment database. For the modern materials category then, k_{mix} = 0.0, while k_{mix} = 1.0 for classic materials category, and 0.0 < k_{mix} < 1.0 for mixed materials. For the mixed materials case, a partial breakup cloud is built by sampling fragments from the two fragment databases separately, which are combined to form the total breakup cloud. Although the database-sampling approach to modeling a breakup cloud is very different from the NASA SSBM, the need to conserve total mass – where the sum of all fragment masses in a simulated breakup cloud equals the input mass – must still be maintained in the sampling approach as in the SSBM.

Database sampling follows the same approach as the NASA SSBM for determining how many breakup fragments to create from 1 mm to over 1 m. A power law predicts the cumulative number of fragments equal to or greater than a given characteristic length (L_C), where L_C is defined as the average of the object's three maximum orthogonal projected dimensions. For collisions, the number of fragments of L_C or larger, in meters, is determined by the SSBM power law [1, 2]:

$$N_{cum}(L_c\ [m]) = S \cdot 0.1\ \cdot \left(\frac{M\ [kg]}{1\ [kg]}\right)^{0.75} \cdot \left(\frac{L_c\ [m]}{1\ [m]}\right)^{-1.71} \tag{1}$$

where S is an empirically derived unitless factor to allow rescaling of the standard power law (applicable to individual space objects or objects belonging to a well-defined class), and M, the collisional mass in kg. For catastrophic collisions, M is the sum of total mass of both colliding objects (the more massive target, M_{target}, and the less massive projectile, M_{proj},). For non-catastrophic collisions, M is defined as:

$$M\ [kg] = M_{proj}\ [kg]\ \cdot \left(\frac{v_{imp}\ [km/s]}{1\ [km/s]}\right)^2 \tag{2}$$

A collision is defined as catastrophic if the ratio between the impact kinetic energy to M_{target} is equal to or greater than 40 J/g. The standard power law (with S = 1.0) prescribes the size of the simulated fragment population for this study. Operationally, a standard implementation of the NASA SSBM will include the distribution of fragments from 1 mm to 1 m, with the fragment distributions subdivided into size regions/bins (widths of every quarter- or half-decade of $\log_{10}(L_c)$ space) from which randomly drawn samples are modeled. For the case of a collision involving two large objects, or objects with relatively comparable mass, the collisional power law is evaluated separately for each object, where M is the mass of each individual object.

During the SSBM breakup-cloud building process, the smallest fragments are generated first, according to the predicted number of fragments for each size region, and their masses are accumulated. The total number of fragments predicted by the power law across all size regions is defined as $N = N_{cum}(0.001)$. The simulation process continues until the accumulated mass reaches M or until N fragments have been created. Because it is possible to simulate N fragments (each of mass m_i) before accumulating the total mass, additional fragment mass δM may need to be added to reach a breakup mass of M, according to:

$$M = \sum m_{i_{[\,power\ law\,]}} + \delta M_{[larger\ fragments\,]} \tag{3}$$

The additional mass δM for debris > 1 m is generated using the same SSBM process, where the remaining mass is partitioned into several fragments in the 1 m-size region with fragment characteristics based on historical breakup behavior [2, 3].

3 Process

A database-sampling approach must follow a similar approach to reaching M operationally. To accomplish this, a materials category is assigned according to the criteria above, and the appropriate impact-fragment dataset (SOCIT for classic materials, DebriSat for modern materials, or mixed) is loaded into machine memory. As part of the database loading process, each sample fragment is assessed for missing or incomplete information before it is loaded; unusable records are ignored, and usable records are sorted by increasing size to correlate which sample fragments belong to which size bin. The database is then sampled, and the characteristics (L_C, mass, cross-sectional area, density category, sampled A/m) of randomly selected fragments become the constituents of the modeled break-up cloud. A sampled A/m is simply the ratio of the sampled area to the sampled mass.

3.1 Database Limits

A limitation of the database sampling approach is that the fragment databases have low numbers of samples at larger sizes (Fig. 1). A sampling size limit is therefore required due to a lack of database samples above a certain size threshold. For this experiment, a sampling size limit was set at the 10-cm level for the SOCIT and DebriSat fragment databases; when the power law predicts fragments larger than this limit, an adaptation of the legacy SSBM simulation process is used. Process-flow pseudo-code for a database sampling approach is outlined in Table 2 against pseudo-code describing the legacy SSBM approach, showing how database sampling leverages the legacy modeling paradigm when the database lacks samples above a certain size.

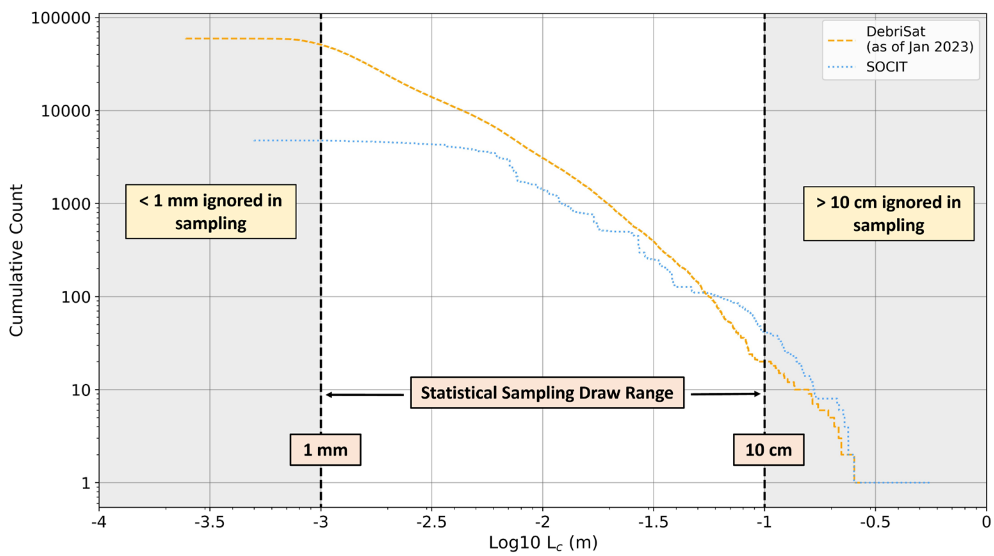

Fig. 1. Cumulative count over L_C for the SOCIT and DebriSat fragment databases. The minimum size of sampled draws is 1 mm, which is consistent with the NASA SSBM power law. A maximum sampling size-limit of 10 cm is adopted.

3.2 Database Sample Blurring

Using the power law starting with size L_C = 1 mm, the number of needed sample fragments is predicted for each size region or bin L_i, defined as N_i. For each size bin, N_i fragments are sampled with replacement. To avoid duplicated fragments in the debris cloud, the characteristics of each drawn fragment are randomly augmented by a relatively small amount or blurred. If blurring simulates a fragment with L_C < 1 mm or simulates a fragment for a size bin expecting no fragments, then the sample is discarded and redrawn. The various properties of the sampled fragment (L_C, mass, area, *etc*.) are physically coupled, so that small deviations to one parameter are also reflected in the other parameters to ensure that they do not contain unrealistic debris objects. Without altering the material density or shape classification, the variations in fragment mass, volume, and area-to-mass ratio due to a deviation of fragment size can be approximated by assuming the fragment is a cylinder with a given length-to-diameter ratio [4].

3.3 Simulation Past the Database Sampling Size-Limit

This fragment simulation process continues until (a) the sampling size-limit of the chosen fragment database is reached, (b) the accumulated mass m_{sum} approaches M, or (c) N_i is reached for each size bin L_i. If the power-law predicts fragments beyond the sampling size-limit of 10 cm adopted for this work, a random size is drawn from a uniform distribution using the edges of the current size bin L_i. Computation of A/m, cross-sectional area, and mass follows the SSBM process described in [1] – given L_C, a random deviate of A/m is drawn from an A/m distribution, the cross-sectional area is calculated as a function of L_C, and the mass equals the area divided by the A/m. This sub-process continues until (a) N_i is reached for each size bin L_i, or (b) the accumulated mass m_{sum} approaches the mass of the parent body target M.

If the total mass from N fragments has not reached M, then the remaining mass δM is partitioned into several large fragments in the > 1 m-size region with fragment characteristics based on historical breakup behavior. If the iterative process reaches a state where $m_{sum} > M$, then a final step is needed to resolve this mass difference. This is done by rescaling the most recently added fragment by $\delta M/m_{last}$, where m_{last} is the mass of the most recently added fragment. This ratio is also used to rescale the last fragment's L_C, area, and A/m.

Table 2. Process Flow Comparison of SSBM and Direct Data Sampling for Simulating a Breakup Event

	SSBM (Analytical)	**Dataset Sampling**
POWER LAW	for i = 1 to [#_of_size_bins] N_i = Eq. (1) if N_i = 0: exit for n = 1 to N_i **SIMULATE FRAGMENTS** $m_{\text{sum}} = m_{\text{sum}} + m_i$ if $m_{\text{sum}} > M$: exit end end	for i = 1 to [#_of_size_bins] N_i = Eq. (1) if N_i = 0: exit for n = 1 to N_i **if L_i < [sampling size-limit]:** **DRAWS FROM IMPACT DATA** **else:** **SIMULATE FRAGMENTS** **end** $m_{\text{sum}} = m_{\text{sum}} + m_i$ if $m_{\text{sum}} > M$: exit end end

LARGER FRAGMENTS	if ($m_{\text{sum}} < M$):
	Partition remaining mass into larger pieces
	end if
	Rescale last added fragment so $m_{\text{sum}} = M$
		if ($m_{\text{sum}} < M$):
		Partition remaining mass into larger pieces
		end if
		Rescale last added fragment so $m_{\text{sum}} = M$

4 Results

A catastrophic collision was modeled as a test of the statistical database approach, using a 10 kg projectile mass colliding with a spacecraft target mass of 990 kg at an impact velocity of 7 km/s. For this work, this breakup is simulated three times. The first simulation uses the SSBM as a baseline. The second simulation is the database sampling model with the materials era category set to classic (k_{mix} = 1.0). The third simulation uses the database sampling model with modern materials era category (k_{mix} = 0.0). The power law (Eq. (1) that fills the number of fragments in each size bin is dependent on size and scale factor. The total number of fragments created from each breakup simulation is expected to vary slightly due to the differences in how the masses are accumulated and the number of large fragments needed for mass conservation. However, the numbers of fragments allotted to each size bin below 10 cm among the three simulated runs are the same as expected. Such values are for exploratory and illustrative purpose; actual breakups in low Earth orbit may be rescaled according to on-orbit data, using a variable value for *S* in Eq. (1), which can significantly alter the number of objects in any size bin.

Fig. 2 shows the number of objects per mass bin for each of the simulated runs. The number of objects per mass bin for the classic-era materials case closely matches the SSBM; however, the case based on modern-era materials has more objects in the lower mass bins by comparison. This is likely related to the overwhelming contribution of low-density (LD) fragments, specifically CFRP fragments of mass $< 10^{6}$ kg, in the DebriSat fragment database [5]. Their large numbers cause repeated resampling on consecutive draws, and as a result, noticeably less mass is accumulated in these lower bins, even though the number of fragments per size bin remains the same by virtue of Eq. (1).

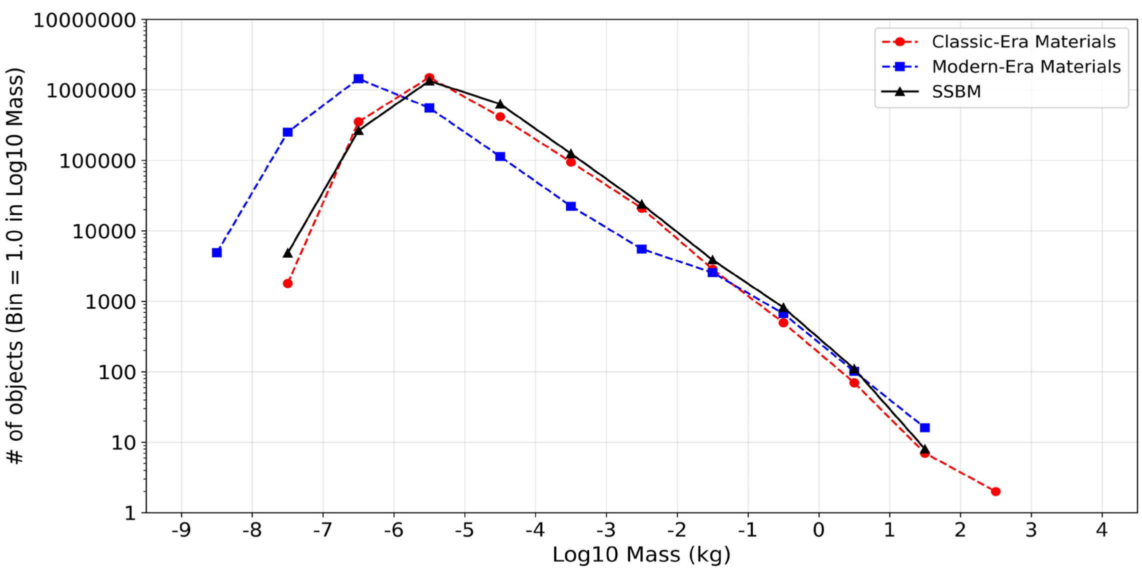

Fig. 2. Number of objects per mass bins of simulated catastrophic collision event for SSBM (black), statistical draws using SOCIT dataset/classic-era materials (red), and statistical draws using DebriSat dataset/modern-era materials (blue). The modern-era materials test case shows a larger number of objects of very-low mass due to the resampling of low-density fragments from the DebriSat dataset.

The number of objects in A/m bins for each of the simulated runs is shown in Fig. 3. The smooth A/m distribution in the SSBM case is from the bi-Gaussian distribution for spacecraft used to derive A/m for a given L_C [1]. Both the classic-era materials case and the modern-era materials case have fewer low-A/m objects compared to SSBM; however, the modern-era materials case has more high-A/m objects than both the classic-era materials case and SSBM. For the classic-era materials case and SSBM cases, the number of objects approaches a maximum at ~ 0.5 m^2/kg and then steadily decreases. For the modern-era materials case, the peak A/m is shifted to ~ 1.7 m^2/kg with an increase in large A/m values (> 10 m^2/kg). Further analysis shows that over 95% of these high A/m objects (> 10 m^2/kg) have a material density < 2 g/cm^3. This is supported by Fig. 4 which shows that a substantial number of high A/m objects in the DebriSat fragment database are LD. This increased number of high A/m objects is coupled with the large number of low-mass objects – a direct consequence of resampling LD fragments (of low mass and high A/m) from the DebriSat fragment dataset.

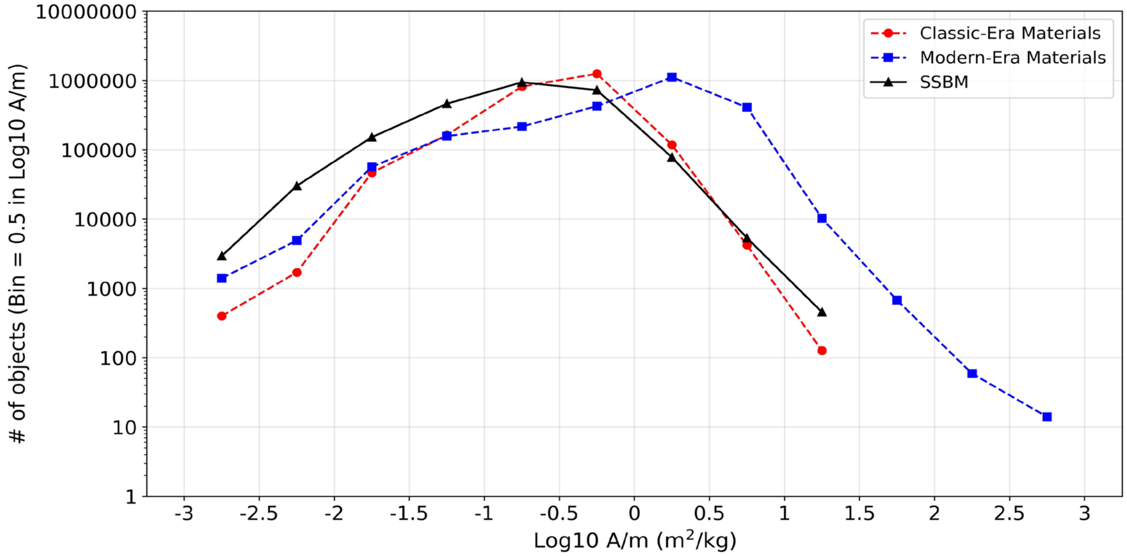

Fig. 3. Number of objects per A/m bins of simulated catastrophic collision event for SSBM (black), statistical draws using SOCIT dataset/classic-era materials (red), and statistical draws using DebriSat dataset/modern-era materials (blue). The resampled low-density fragments of very low mass have very high A/m (> 30 m^2/kg).

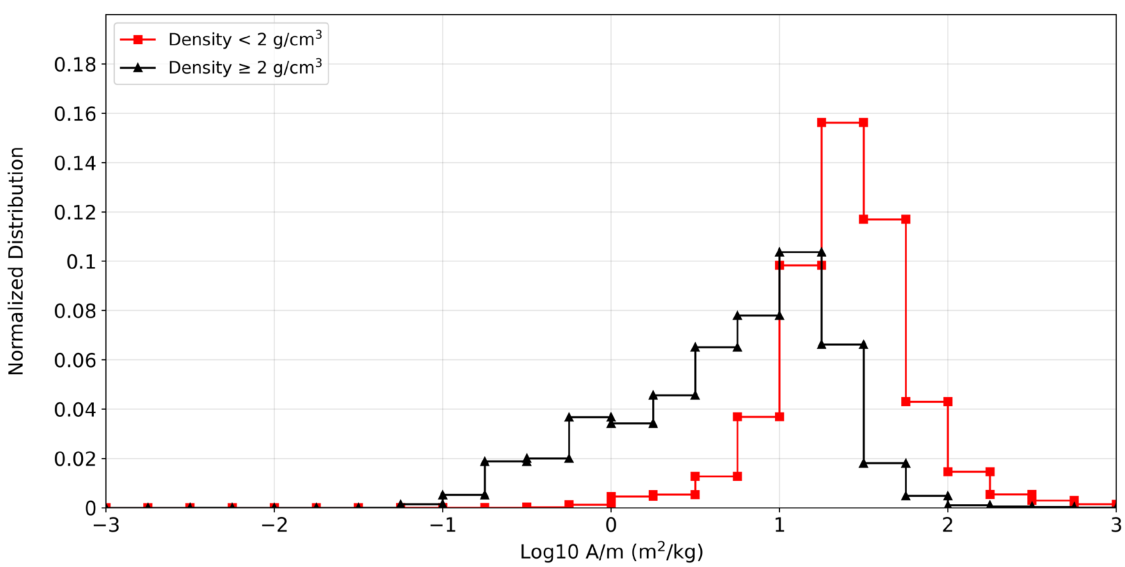

Fig. 4. Normalized distribution of the number of objects per A/m bins in the DebriSat fragment database. The overwhelming majority of high A/m objects are low-density, specifically CFRP.

To further study the effect of LD fragments (MLI, plastics, CFRP, GFRP) in the database-sampling approach, two additional breakups were simulated. One simulation employed database sampling of classic-era materials (SOCIT-based) while ignoring all low-density fragments. The other simulation employed database sampling of modern-era materials (DebriSat-based), also without low-density fragments.

Fig. 5 show the mass distributions of classic-era and modern-era materials test cases without low-density fragments, compared to SSBM. Relative to Fig. 2, the first two bins (mass < 10^{-7} kg) of the modern-era materials test case show a drop in the number of objects by an order of magnitude. Ignoring low-density fragments in the SOCIT dataset has a negligible effect on the mass distribution compared to the previous classic-era materials test case. For the modern-era materials case, the mass distribution now closely resembles the SSBM and classic-era materials cases.

The A/m distribution of classic-era and modern-era materials test cases without low-density fragments, compared to SSBM is shown in Fig. 6. Ignoring low-density fragments in the SOCIT dataset has a negligible effect on A/m; however, for the modern-era materials test case, the number of high A/m objects has dropped significantly, and the distribution closely resembles the classic-era materials case.

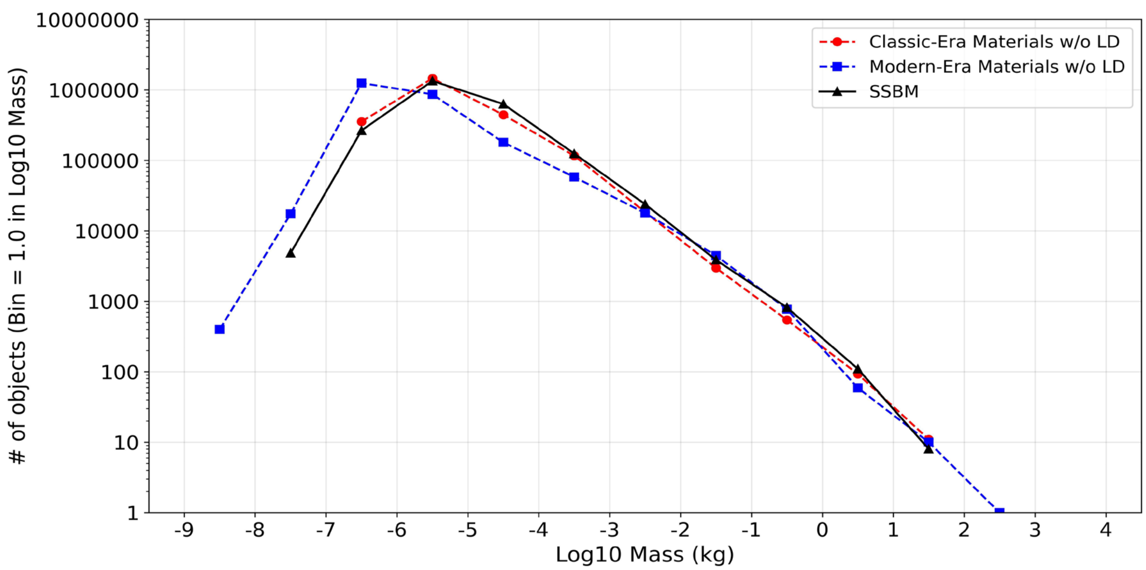

Fig. 5. Number of objects per mass bins of simulated catastrophic collision event for SSBM (black), statistical draws using SOCIT dataset/classic-era materials without the resampling of low-density fragments (red), and statistical draws using DebriSat dataset/modern-era materials without the resampling of low-density fragments (blue). Both database sampling test cases yielded a mass distribution that agrees with SSBM.

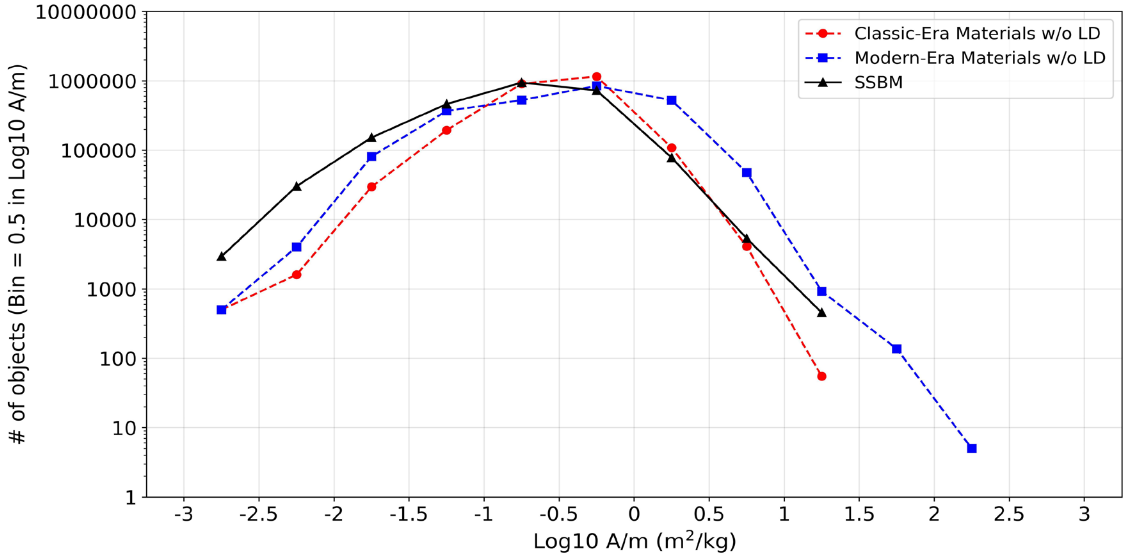

Fig. 6. Number of objects per A/m bins of simulated catastrophic collision event for SSBM (black), statistical draws using SOCIT dataset/classic-era materials without the resampling of low-density fragments (red), and statistical draws using DebriSat dataset/modern-era materials without the resampling of low-density fragments (blue). Both database sampling test cases have a similar A/m distribution.

Though the numbers of fragments generated in the 1 mm- to 10 cm-size range of statistical draw model remain mostly the same for each simulated run, the mass accumulated will vary depending on the model, as shown in Table 3. When the SOCIT dataset is used for sampling (*i.e.*, classic-era materials), 48.3 kg is accumulated in the 1 mm- to 1 cm-size region, which is 40% less mass compared to SSBM in the same number of fragments. When the DebriSat fragment database is used for sampling (*i.e.*, modern-era materials), there is a 90% decrease in mass in the 1 mm to 1 cm size compared to SSBM. For size region 1 cm to 10 cm, the accumulated mass for the modern-era materials and classic-era materials are similar, although not as high compared to SSBM. Ignoring LD fragments from resampling for the classic-era materials test cases has a minor effect on the total mass for objects less than 10 cm. For the modern-era materials test cases, objects less than 10 cm accumulated 74% more mass when LD fragments are ignored relative to when they are included.

Table 3. Accumulated Mass Per Size Region for the Simulated Catastrophic Collision Event

Model	**SSBM**	**Database Sampling**			
Materials Category	-	Classic-Era	Classic-Era, w/o LD	Modern-Era	Modern-Era, w/o LD
Mass (kg), 1 mm to 1 cm	83.7	48.3	47.5	9.1	22.1
Mass (kg), 1 cm to 10 cm	389.3	195.0	205.5	197.9	337.9
Mass (kg), > 10 cm	527	756.7	747	793	640

5 Conclusions and Future Work

With the availability of fragment databases representing different eras, the generational design paradigms and material composition of a parent body will become important to the accurate portrayal of future on-orbit breakup events. For classic-era materials, the simulated mass distribution from the database sampling method employing the SOCIT fragmentation data is shown to be like the SSBM, which is expected because the analytic equations of the SSBM are originally based in part on the SOCIT fragmentation data. For modern-era materials, the simulated mass distribution from the database sampling method based on the DebriSat data demonstrates many more low-mass fragments at smaller sizes than the SSBM and classic-era materials results. The increased numbers of small, low-mass fragments for the modern-era have a reciprocal effect to drive up the numbers of high A/m fragments at smaller sizes.

When low-density fragments (< 2 g/cm^3) are removed from the fragment datasets, the distributions of mass and A/m of SSBM, modern-era materials, and classic-era materials better resemble each other. This suggests that the lowest density fragment populations, dominated by CFRP for DebriSat, might need to be handled differently in the future. One approach might investigate a new fragment count power law or scale factors to compensate for the larger numbers of small, low-density fragments, especially in modern-era materials, that are not well represented by the standard power-law. A substantial data-driven revision of the single power law would lessen the burden of re-scaling using radar observation data.

6 References

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