Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 54 (2014) 1479–1486
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

Experimental study of impact-cratering damage on brittle cylindrical column model as a fundamental component of space architecture

Akira Fujiwara [a,*], Naomi Onose [b], Masato Setoh [c], Akiko M. Nakamura [c], Kensuke Hiraoka [c], Sunao Hasegawa [b], Kyoko Okudaira [d]

[a] 29 Tsukamoto-cho Shimogamo, Sakyo-ku, Kyoto 606-0856, Japan
[b] Institute of Space and Astronautical Science, Sagamihara, Kanagawa 252-5210, Japan
[c] Kobe University, Kobe 657-0013, Japan
[d] Aizu University, Aizu-Wakamatsu 965-8580, Japan

Received 5 September 2013; received in revised form 6 June 2014; accepted 10 June 2014
Available online 18 June 2014

Abstract

The cylindrical column of brittle material processed from soil and rock is a fundamental component of architectures on the surface of solid bodies in the solar system. One of the most hazardous events for the structure is damaging by hypervelocity impacts by meteoroids and debris. In such a background, cylindrical columns made of plaster of Paris and glass-bead-sintered ceramic were impacted by spherical projectiles of nylon, glass, and steel at velocity of about 1–4.5 km/s. Measured crater radii, depth, and excavated mass expressed by a function of the cylinder radius are similar irrespective of the target material, if those parameters are normalized by appropriate parameters of the crater produced on the flat-surface target. The empirical scaling relations of the normalized crater radii and depth are provided. Using them, crater dimensions and excavated mass of crater on cylindrical surface of any radius can be predicted from the existing knowledge of those for flat surface. Recommendation for the minimum diameter of a cylinder so as to resist against a given impact is provided.

Keywords: Space architecture; Crater; Hypervelocity-impact; Cylinder, Brittle material; Space engineering

1. Introduction

With increasing human activities in space, construction of variety of architectures which make human beings' living on planets, satellites, and minor bodies possible are coming into our realistic scope, and search of candidate materials and performance tests of various kinds of fundamental components for those architectures have come to be required. Many kinds of structural components made of lithic brittle materials such as mortar, brick, ceramic, or glass used in traditional civil engineering on the earth are also hopeful on the planetary surface, because such materials can be supplied through on-site processing of soil and rock which are abundant and easy to get on the surface of inner solar system bodies. One crucial factor bringing serious damage on those components on the planetary surface is the meteoroid impact. Hence it is indispensable to prepare database on impact damage on the architecture's fundamental components such as plate, cylindrical and rectangular column of various brittle materials, and those data should be systematically taken and

* Corresponding author. Fax: +81 075 791 3275.
E-mail address: hfujiw@gf6.so-net.ne.jp (A. Fujiwara).

http://dx.doi.org/10.1016/j.asr.2014.06.015
0273-1177/

archived, and finally standardized for the practical use in engineering. Our present work is the first step toward this goal.

There exist many works on impact cratering on semi-infinite and plate targets (for example see Kinslow, 1970; Zukas, 1990; McDonnell, 1992, and references therein), but data on cratering on the column of brittle material, which is also the fundamental component in practical point of view, are very limited. It is not clear that on the cylindrical column surface how much the cratered zone extends toward the lateral and backside zone and how much the column strength is weakened. In this paper we experimentally clarify the extent of cratering damage on cylindrical columns of brittle material by hypervelocity impact as the first step toward the above mentioned goal. We especially aim to clarify a morphological relationship between the crater on the cylindrical column and that on the semi-infinite flat surface produced under the same impact condition other than the target shape, because study of cratering on the flat-surface targets of brittle material has a long history among planetary scientists, and at present numerical simulation and scaling relations have been well developed although they are still in progress (for example, Roddy et al., 1977; Melosh, 1989, references therein).

In this paper under the above scheme we report impact experiments using cylindrical column targets made of plaster of Paris (plaster) and glass-bead-sintered ceramic (GBC). Plaster and GBC are adopted as a model material of brittle material which are composed of simple ingredient and easily available in the laboratory. Both materials have low density and we can know the density dependence of the result by comparing similar experiment using mortar cylindrical targets Fujiwara et al. (1993). Experiments using flat surface targets were also performed to compare with the ones for cylindrical columns. Experimental procedure is given in Section 2, and the data are presented in Section 3. Discussion and conclusion are given in Sections 4 and 5, respectively.

2. Experiments

Cylinders made of plaster of Paris (hereafter simply called plaster), and sintered glass bead ceramic (GBC) were prepared. Plaster targets were manufactured by molding the powdery plaster mixed with water into cylindrical shapes. They were dried in the free air for weeks until their weight did not decrease any more. For detailed information, see Onose (2007). Radius a of the cylindrical targets ranged from 5.5 to 30 cm and length from 9 to 21 cm. Density of the plaster targets was $0.920 \pm 0.040\ \mathrm{g/cm^3}$, uniaxial compressive strength 12 ± 1.7 MPa, sound velocity 2200 ± 150 m/s (measured by pulse transmission). and porosity 60%. Tensile strength is estimated to be about 1.0 MPa by the extrapolation of Vekinis et al. (1993) data, which give the tensile stress of plaster of Paris as a function of density.

GBC targets were fabricated similarly as reported in Love et al. (1993) by sintering bulk of glass beads in a cylindrical mold set in an oven. Detailed data for the temperature and duration for the heating are seen in Setoh et al. (2010). Radii of the cylinders were 3.0 and 5.0 cm. Length of GBC cylinders is about 10 and 6 cm. Density is $1.46 \pm 0.05\ \mathrm{g/cm^3}$. Tensile stress was 1.15 ± 0.15 MPa, which was calculated from the value of radial compressive load under which the cylindrical disk samples start to split (called Brazilian test). Compressive strength was obtained to be 17.3 ± 2.7 MPa from uniaxial compression test,

Impact experiments were performed using a two-stage light-gas gun at the facility of ISAS/JAXA. Lateral surfaces of plaster targets were impacted at normal incidence by spherical projectiles of nylon (diameter $s = 0.7$ cm, mass $m_p = 0.21$ g) and GBC targets by glass spheres ($s = 0.32$ cm, $m_p = 0.043$ g) and stainless-steel sphere (diameter 0.16 cm, mass 0.017 g), respectively, at velocity ranging from 1.5 to 4.5 km/s in evacuated state. Here we used those projectile materials by following reasons. Nylon is not only a representative of the low density material but also can be compared with former experimental results by Fujiwara et al. (1993) performed by using the same projectile material. Glass bead was used as a stimulant of rocky meteoroid material, because glass bead is composed of silicate and similar density. Stainless steel was used as a stimulant of iron meteoroids or artificial debris materials, although our experimental runs are limited and exploratory. Experimental conditions are summarized in Table 1A (PN and GG series). Targets with flat surface were also prepared using the same material as used for the cylindrical targets and, the same projectiles (excluding the stainless projectile) were impacted to compare with the cylinder series. The experimental condition is shown in Table 1B (PFN and GFG-1 and 2). After the impacts, dimensions of the cratered zone on the targets were measured in the following way. We rolled a sheet of semitransparent paper on the lateral side of the cylinder and traced the rim shape on it. After removing the paper from the target surface, we measured the radius every ten degrees around the impact point, and averaged the four radii in directions selected symmetrically from four quadrants around the center.

Along with our experimental data we also use crater data on nortar spherical- and flat-surface targets shot by nylon spheres from Fujiwara et al. (1993) (run code MN-F and MFN-F, respectively), and crater data on GBC flat-surface targets shot by glass beads from Hiraoka (2008) (GFG-H). Diameters of both projectiles are the same as in our experiment. Those experimental conditions are included in Tables 1A and 1B. In those tables, shock pressures estimated for all runs are shown (Pressures for plaster and GBC were determined by method by Onose (2007) and Hiraoka (2008), respectively). A meaningful parameter to compare cratering outcomes on different materials is the pressure normalized by tensile strength, and it ranges 4.9×10^{-3}–1.7×10^{-2}, 1.0×10^{-3}–6.2×10^{-3}, and 6.0×10^{-3}–8.0×10^{-3} for PN, GG, and MN series, respectively (Since the tensile strength of mortar is not