International Journal of Non-Linear Mechanics 67 (2014) 133–143

Contents lists available at ScienceDirect

International Journal of Non-Linear Mechanics

journal homepage: www.elsevier.com/locate/nlm

Microscopic measurements of planar viscoelastic body eccentric impacts on a convex corner

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ARTICLE INFO

Article history:
Received 25 February 2014
Received in revised form
26 August 2014
Accepted 28 August 2014
Available online 9 September 2014

Keywords:
Impact motion
Impact ratio
Stiffness
Friction
Deformation
Bounce-off angle

ABSTRACT

This paper presents the effects of the target edge shape on eccentric impact motions, which were experimentally investigated by concurrently measuring the microscopic deformation of the target edge around a contact point and the global trajectory. This study is important for understanding the impact motions that occur between viscoelastic deformable polygonal objects with friction. The materials used in this experiment were four types of resin and one metal; four convex shapes and one circular shape were used for the impacted target plate. Interestingly, anomalous trajectories of the impact plate that varied with the target edge shape were found beyond the regime of rigid body dynamics, and were strongly dependent on the tangential deformation of the edge. In addition, it was found that the tangential deformation amount had a correlation with the bounce-off angle of the impact body for all materials used. That is, the target edge had a weaker tangential stiffness with sharpening of the edge shape, and thus, remarkably, absorbed the tangential impact energy as strain energy, due to a tangential deformation of the edge. Consequently, the bounce-off angle of the elastic body became smaller than that generally expected from rigid body dynamics, and sometimes even became negative because the direction of the contact force is significantly changed with increase in the tangential deformation of the edge.

1. Introduction

An exact understanding of the impact behavior of viscoelastic polyhedrons is enormously important for estimating and controlling actual multi-body motions in civil engineering and disaster prevention research, which deal with problems such as rockfall and the design of structures where objects have irregular shapes; spherical objects are rare. The primary characteristic of the impact motion for viscoelastic polyhedrons is that the microscopic elastic deformation around the contact point of the collision influences the subsequent trajectory to varying degrees. Moreover, the deformation properties around the contact point depend on the local mechanical properties, such as the stiffness and viscous damping, that depend on the edge shape if the collision occurs on the edge of a polyhedron. Therefore, to accurately estimate the impact motions of viscoelastic polyhedrons, we need to investigate the relationship between the trajectory and the microscopic deformation around a contact point in detail.

In recent years, a number of numerical simulation methods for impact problems involving polygons or polyhedrons have been developed [1], including some analytical methods based on impulsive force [2] and penalty methods, i.e., a discontinuous deformation analysis [3,4], a bonded particle method [5–7], a discrete (distinct) element method [8–13], and the combined finite element method [14]. For the analytical methods, the object motions are calculated from the estimated velocity after collision based on the impulsive force between the two objects, which sometimes takes into consideration not only the normal force but also the frictional force. On the other hand, penalty methods calculate the object motions on the basis of the contact force estimated from a contact force model, e.g., the spring-dashpot model, using an artificial amount of overlap between the objects in contact. In either method, an accurate estimation of the force vectors between the objects is important for simulating the actual motion.

On this point, a number of theoretical and/or experimental studies have been done in order to clarify the motions of impacting bodies while taking inelasticity and friction into consideration [15–19]. Some of the studies were executed for oblique impacts of a spherical body or a circular plate against a flat plate on the basis of rigid body dynamics [20,21]. In these studies, the ratio of the tangential to the normal impulse was treated as the frictional coefficient in the case of a fully sliding contact surface. When deriving the coefficient of restitution, anomalous situations were reported in which the normal restitution coefficient exceeded

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http://dx.doi.org/10.1016/j.ijnonlinmec.2014.08.015

unity [22,23] or became negative [24,25]. The knowledge obtained from these studies has helped us to increase the accuracy of numerical simulations of the impact problem. However, the impact problem is very complex and these frictional collision behaviors depend on whether the contact surface is sliding or sticking in the compression and/or the restitution phase, and whether the contact surface is sliding fully or partially. In addition, a lack of microscopic measurements around the contact point hampers understanding of these impact problems. Therefore, the predictions about the frictional collision behavior unfortunately vary from model to model.

In comparison with the influence of the friction and restitution coefficients, the influence on the motion of the object arising from the contact point deformation due to elasticity has not been widely investigated. Moreover, there has been very little experimental study of the frictional collision behavior of polygon or polyhedron impacts. These irregularly shaped objects are often treated in the same way as spherical or circular objects, i.e., with the frictional coefficient set to be equal to the impulse ratio. However, the edge deformation properties arising from the shape and the stiffness potentially influence the impulse ratio and the restitution coefficient; this is a primary point of this paper, as our results demonstrate that the edge properties can indeed have such an influence. In fact, when we previously estimated the frictional collision behavior of a polygon plate using a discrete element method (DEM) simulation with a frictional coefficient obtained from the experimentally measured impulse ratio, the trajectory did not agree with the experimental one [26]. In order for the simulated trajectory to agree with the experimental one, the frictional coefficient had to be set to be smaller than the impulse ratio. However, we did not understand this result because we could not observe the microscopic behavior around the contact point in sufficient detail.

In this paper, both global observations of the translational and rotational motions and also microscopic observations around the impact contact point with a spatial resolution four times higher than that of past work were obtained simultaneously. For the frictional impact motion of a square plate against a convex edge, the influence of the elastic deformation due to the convex edge properties such as the stiffness and the coefficients of restitution and friction was investigated through microscopic measurements. Finally, the mechanisms of the trajectory changes which depend on the edge properties were clarified by examining the relationship between the bounce-off angle and the edge deformation.

2. Experimental methods

We measured and analyzed the two-dimensional impact motions of a planar body against a corner for various convex and circular shapes. The apparatus and materials used in the experiment and the experimental procedure are described below.

2.1. Apparatus

The schematic of the experimental apparatus is shown in Fig. 1(a). On an air table, a square impactor was shot straight towards a target plate at a constant velocity using a linear actuator (EZA6D030M-K, ORIENTAL MOTOR Co., Ltd.). In this setup, the impactor maintained an effectively frictionless planar motion on the air table. The target plate was fixed to a heavy (2.0 kg) metal block bolted to the air table, which was treated as infinitely massive in the subsequent analysis. The metal block is made of 18/8 stainless steel (the density, Young's modulus, and Poisson ratio are 7930 kg/m^3, 193 GPa, and 0.3, respectively) and its geometry is shown in Fig. 1(b). Note that the stainless steel, which is a heavier material than that used for the square impactor and the target plate, was applied in order to keep the target plate as stable as possible when the impactor collided with the target plate. The two-dimensional impact motions between the impactor and the target edge on the air table were captured using two high-speed video cameras. One video camera (FASTCAM-1024PCI, PHOTRON Ltd.) had a wide angle lens (Ai Nikkor 20 mm f/2.8S, NIKON Co.) and so was used to capture the global motion of the impactor. The other camera (FASTCAM-SA1.1, PHOTRON Ltd.), which had a microscope lens attached (VH-Z100R, KEYENCE Co.), was used to capture the local behavior at the contact point between the impactor and the target plate. A metal-halide lamp (LS-M210, SUMITA OPTICAL GLASS, Inc.) was attached to the microscope lens, providing an epi-illumination system which allowed clear, ultra high-speed recording of the microscopic behavior through the microscope lens. Moreover, in order to achieve a sharper focus, the ultra high-speed video camera was attached to a positioning stage (TSD-605S, SIGMA KOKI Co., Ltd.) which permitted focus adjustments at a resolution of 0.003 mm, even though the microscope lens has a shallow depth of field.

2.2. Impactor and target characteristics

The shapes of the target plates are shown in Fig. 2. The target plates have a thickness of 5 mm. Two types of target edge contact

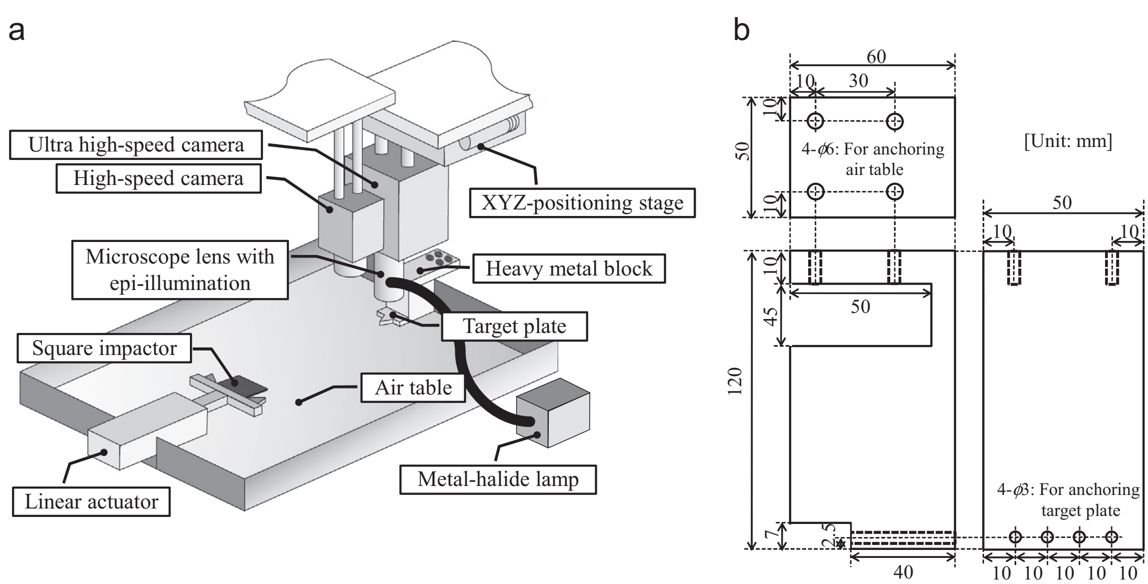

Fig. 1. Experimental apparatus: (a) overview and (b) geometry of the heavy metal block used to anchor the target plate.