International Journal of Solids and Structures 62 (2015) 81–90

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Plastic waves in one-dimensional heterogeneous granular chains under impact loading: Single intruders and dimer chains

Tommy On, Erheng Wang, John Lambros *

Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, 104 South Wright Street, Urbana, IL 61801, USA

ARTICLE INFO

Article history:
Received 3 August 2014
Received in revised form 20 December 2014
Available online 12 February 2015

Keywords:
Contact
Heterogeneous granular chain
Dimer
Plasticity
Intruder

ABSTRACT

Elastic granular dimer chains (defined as arrays of repeating dissimilar material granule pairs) have shown promise for wave mitigation applications since it has been observed that for certain dimer mass ratios significant force attenuation can occur along the chain during dynamic wave propagation (Jayaprakash et al., 2013). However in many applications, applied forces are likely to be such that the elastic assumption would be violated at locations of high stress concentration – the granule contact points. In this work we seek to investigate the force transmitted through dimer chains and chains with a single intruder (i.e., differing granule from the surroundings), subjected to dynamic loading in the plastic regime. A split Hopkinson pressure bar was used to dynamically load one-dimensional metallic dimer chains and homogeneous chains of metallic spheres with single intruders. Loading magnitudes ranging from 10 kN to 35 kN were applied to these chains, producing significant plasticity in the beads. The results in each case were quantified by the ratio of the output to incident force from the granular chain. Transmitted force results were compared to those in elastic dimer chains for which force attenuation was controlled by the mass ratio of the dimer pair. In the plastic case, however, the propagating pulse was found to have a strong dependence on the yielding material, not on the dimer mass ratio. Although output force was significantly reduced over input force, the reduction was driven by plastic dissipation and not elastic attenuation mechanisms. Chains with a single intruder were also seen to behave differently when the intruder was relatively softer or harder than the remainder of the chain. For a softer intruder the transmitted force decreased as the intruder location moved further down the chain, while for a harder intruder the output force did not depend on intruder location and was roughly the same as that of a homogeneous chain, i.e., the harder intruder did not affect wave transmission.

1. Introduction

A one-dimensional (1D) granular chain array can be thought of as a series of spheres in contact. It is known that such 1D systems are able to support solitary waves under dynamic loading (Nesterenko, 1984, 1992, 2001; Lazaridi and Nesterenko, 1985; Nesterenko and Lazaridi, 1987; Gavrilyuk and Nesterenko, 1993), and have been extensively studied both numerically (Manciu et al., 1999; Chatterjee, 1999; Rosas and Lindenberg, 2004) and experimentally (Shukla et al., 1990, 1993; Shukla, 1991; Coste et al., 1997; Coste and Gilles, 1999; Daraio et al., 2006; Sen et al., 2008; Carretero-Gonzalez et al., 2009) for elastic chains, and more recently for plastic chains (Wang et al., 2013; On et al., 2014; Pal et al., 2013, 2014). Solitary waves, which in the elastic case form as a result of the nonlinear interaction between beads caused by their Hertzian contact response, propagate along the 1D array without any distortion such as would arise in a continuous medium wave guide from dispersion. In the plastic case solitary-like pulses have also been seen to occur, although in this case plastic dissipation causes a significant amplitude decay as the wave propagates along a 1D granular chain (Pal et al., 2013; On et al., 2014).

Two different 1D granular chains in contact, or one granular chain and one elastic medium in contact, have been seen to exhibit phenomena such as energy trapping and anomalous reflections (Nesterenko et al., 2005; Daraio et al., 2006; Porter et al., 2009; Jayaprakash et al., 2011, 2012, 2013; Pal et al., 2015). Dimer chains, referred to as a 1D granular system composed of two dissimilar beads – either in mechanical properties, density, or size – alternating periodically, have also been studied in the elastic dynamic loading regime both analytically and experimentally (Jayaprakash et al., 2011, 2012, 2013; Potekin et al., 2013). In these works it was found that cases of resonance in these dimer systems can lead to strong attenuation of the propagating pulse depending on the

* Corresponding author.
E-mail address: lambros@illinois.edu (J. Lambros).

http://dx.doi.org/10.1016/j.ijsolstr.2015.02.006
0020-7683/

two granules comprising the dimer system. For example in Jayaprakash et al. (2011) it was shown that in the elastic dimer case the peak pulse force transmitted through the chain depends strongly only on the mass ratio, ε, of lighter to heavier bead. For specific mass ratios of the dimer unit cell significant reduction in the transmitted peak force through the dimer chain was seen. In contrast, for other mass ratios a significant increase in transmitted peak force was observed. In the cases of maximum peak force of the pulse occurring, a solitary wave was seen to propagate along the dimer chain, while when a minimum peak force was observed a new class of waves with long oscillatory force trains were identified. The reason behind this "peak and valley" force dependence on mass ratio is the occurrence of anti-resonance and resonance modes respectively in which the lighter beads moves either in phase or out-of-phase with the heavier beads on either side of it. In the latter case, the out-of-phase motion introduces significant force attenuation at higher frequencies causing the resulting transmitted peak force of the primary pulse to significantly decrease (although in the process numerous trailing load oscillations of much smaller amplitude occur since the system is elastic and no energy is actually dissipated). Nonetheless, such behavior presents an interesting mechanism for possibly controlling the peak transmitted force through a dimer granular 1D chain.

However, in many possible applications that may use such a chain, yielding at the contact points (or another type of nonlinear/failure mechanism in the case of non-metallic beads) may occur. In fact, assuming Hertzian contact theory and a von Mises type yield criterion (Johnson, 1985), one can easily calculate that for realistic materials and sizes the yield load at the contact points of an elasto-plastic granular constituent will be on the order of a few 10's or perhaps 100's of Newtons. For example, in homogeneous chains the initial yield load level for a contact between brass alloy 260 beads with 10 mm diameter is about 5 N, and between stainless steel 440C beads with 25.4 mm diameter it is about 500 N. The result under dynamic loading is a significant pulse peak force decay in the case of ductile granular media deforming plastically, at least for the case of homogeneous granular arrays (Pal et al., 2013; On et al., 2014). In the case of dimer granular chains that deform plastically it is of interest, therefore, to determine if the resonance and anti-resonance modes identified for the elastic dimer system will still occur, and in what way, if any, would plastic dissipation alter these modes. In an earlier study we had experimentally obtained the response of individual dimer pairs both statically and dynamically (Wang et al., 2013). In that work we had shown that both plasticity and material rate dependence can significantly affect the dimer "contact law", including which material of the two dimer constituents would yield. The present effort extends the single dimer pair study of Wang et al. (2013) to (a) dimer chains, i.e., chains of repeating dimer unit cells, and (b) single intruder chains, i.e., otherwise homogeneous chains with a single granular particle of different properties placed somewhere along the length. An understanding of the response under impact loading of both plastically deforming and heterogeneous granular chains can lead to determining the dominant energy mitigation factors present in these systems thus opening the door for their use in high-load impact applications.

2. Experimental procedure

2.1. Experimental setup

A split Hopkinson (or Kolsky) pressure bar (SHPB) (Kolsky, 1949), modified with the addition of a momentum trap (Nemat-Nasser et al., 1991), shown schematically in Fig. 1, was used to characterize the dynamic mechanical response of granular chains. The momentum trap, incident, transmission, and striker bars used in our study are manufactured from C350 maraging steel. The incident, transmission, and striker bars have a diameter of 12.7 mm (0.5 in) and lengths of 3.048 m, 1.829 m, and 0.1524 m, respectively. Strain gauges were placed in the middle of the incident and transmitted bars, and on opposite surfaces to cancel strain readings caused by possible bending of the bars. All strain gauges were connected through a signal conditioner and the output was sent to an Agilent Technologies digital oscilloscope. Typical signals recorded from the strain gauges are shown in Fig. 2.

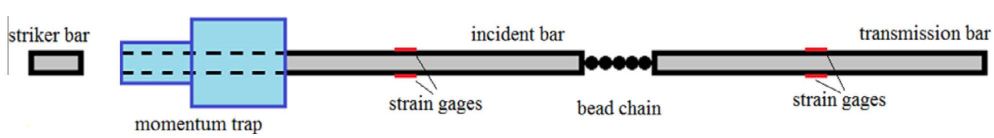

Fig. 1. Schematic of the split Hopkinson pressure bar experimental setup for use with a 1D granular chain.

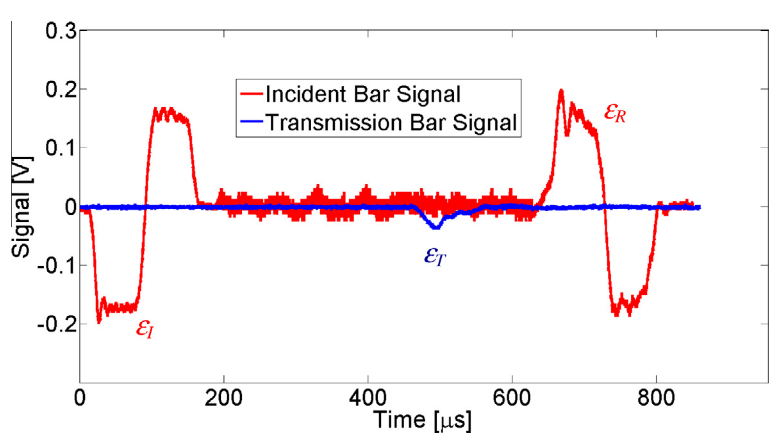

Fig. 2. Raw signals recorded by the strain gauges on the incident and transmission bars during a granular chain impact loading experiment in the SHPB. Note the relatively low transmitted signal resulting from significant plastic dissipation in the granular chain.