Energy Trapping and Shock Disintegration in a Composite Granular Medium

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We report the first experimental observation of impulse confinement and the disintegration of shock and solitary waves in one-dimensional strongly nonlinear composite granular materials. The chains consist of alternating ensembles of beads with high and low elastic moduli (more than 2 orders of magnitude difference) of different masses. The trapped energy is contained within the "softer" sections of the composite chain and is slowly released in the form of weak, separated pulses over an extended period of time. This effect is enhanced by using a specific group assembly and precompression.

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Strongly nonlinear systems, e.g., one-dimensional chains of beads, exhibit unique wave dynamics [1] especially at the interface of two different granular systems [1–6] or at the interface of granular and solid media [7]. The strongly nonlinear wave behavior in a chain of elastic spherical beads arises from the nonlinearity of the Hertzian contact interactions between the particles in the system resulting in a power-law–type dependence of the compressive force (F) on the displacement (δ) (where $F \propto \delta^{3/2}$) combined with zero tensile strength. In the case of zero or very weak precompression this system supports a qualitatively new solitary wave [1]. A peculiar property of this media derives from the possibility of "tuning" the type of solitary waves in the system by varying its precompression [1,8,9]. This allows "choosing" the regime of wave propagation from strongly to weakly nonlinear.

Granular matter has many known applications, but it is difficult to understand its intrinsic dynamic properties due to the strong nonlinearity of forces between particles and their complex distributions [1,10–12]. In the past, the design of shock protectors focused mainly on the wave transformation provided by layered systems or porous media [1,13,14]. Yet an entirely different way of protecting materials is through the confinement of an impulse in a particular region of the shielding medium called a "*granular container*" using a series of sections with particles interacting according to different contact forces and masses as predicted by theoretical analysis [3,4], but not experimentally demonstrated.

The idea of the impulse confinement in our case is based on the anomalous features of an incident wave interacting with an interface between two different chains of stainless steel and polytetrafluoroethylene (PTFE) beads [5]. It was shown that a solitary wave passing from the stainless steel side transmits all of its energy through the interface into the PTFE section. Furthermore, the transmitted signal disintegrates into a sequence of solitary waves [see Fig. 1(c) of [5]]. On the other hand, when a solitary wave approaches the same interface from the PTFE side, numerical calculations and experiments have shown that a significant part of the incident pulse's energy is reflected back into the PTFE side. The amplitude of the reflected solitary wave is ~75% of the incident wave's amplitude and the pulse transmitted to the stainless steel chain decomposes into a train of three solitary waves. In this study we tested experimentally and numerically a granular system composed of sections of stainless steel and PTFE beads with a constant overall number of particles and a fixed ratio between them. We introduced multiple interfaces between sections to enhance the protection of the wall. A material with a similar dynamic behavior can also be made from different structural elements with strongly nonlinear interactions.

To create the granular system for pulse trapping and protection of the wall, we used 32 beads with diameter ~4.76 mm, of which 22 were the high-modulus, large mass stainless steel beads (nonmagnetic, 316 type) and 10 were the low-modulus, small mass PTFE beads [15]. The mass of the 316 stainless steel bead was 0.45 g, with a density of 8000 kg/m^3, Young's modulus of 193 GPa, and the Poisson ratio equal to 0.3 [16,17]. The mass of a PTFE bead was 0.123 g, the density 2200 kg/m^3, the elastic modulus 1.46 GPa, and a Poisson ratio 0.46 [15,18,19]. Three piezosensors were embedded inside the particles as described in [5,9,15] allowing the calculations of the pulse speed. A fourth sensor was embedded in the wall at the bottom of the chain as in [20]. The particles were assembled in a vertical PTFE holder. Single solitary waves were generated with a 0.47 g Al_2O_3 rod striker and shock-type pulses with a 63 g Al_2O_3 rod. In order to tune the properties of the granular protector, a magnetically induced noncontact compressive force (2.38 N) was applied [5,9].

First, a granular protector with a single soft central PTFE section was tested [Fig. 1(a)]. Here, 11 stainless steel beads were placed on top, 10 PTFE beads in the middle, and 11 steel beads at the bottom of the chain. The corresponding impulse behavior is presented in Figs. 1(b) and 1(c) for different incident waves.

To qualitatively compare the experimental results with [4], similar tests were conducted exchanging the particle's positions. Here, 5 PTFE particles were set on the top and

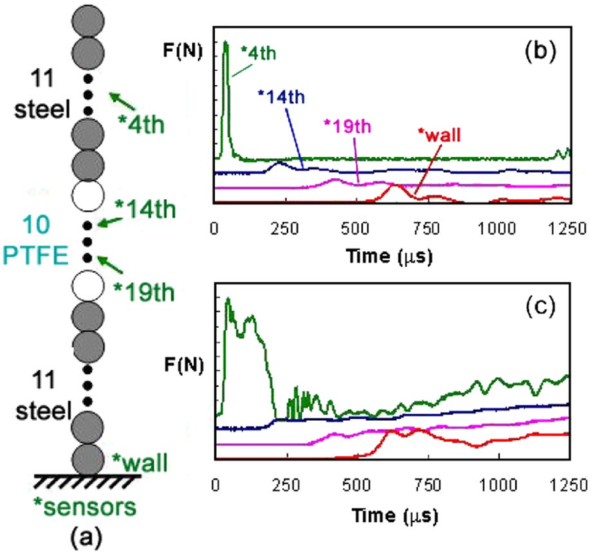

FIG. 1 (color online). Trapping of pulses in the granular protector with a single PTFE section. (a) Schematic diagram of the experimental setup with indicated sensors. (b) Experimental data for the incident solitary pulse. The striker was an Al_2O_3 cylinder of 0.47 g with an impact velocity of 0.44 m/s. (c) Experimental data for the incident shocklike pulse excited by an Al_2O_3 striker (63 g). The *y*-axes scale is 1 N per division for (b) and (c).

bottom sections of the chain and the 22 stainless steel beads were positioned in the middle [Fig. 2(a)]. This configuration can be compared to half of the granular container presented in Fig. 2(c) of [4]. The experimental and numerical results are presented in Figs. 2(b) and 2(c).

The granular protector in Fig. 3(a) had two sections of 5 PTFE particles interposed between the stainless steel beads creating a larger number of interfaces in comparison with Figs. 1(a) and 2(a).

Numerical analysis of the discrete chains was performed for all the setups described to calculate force-time curves as well as the total energy trapped and released by the granular containers. The numerical simulations were run similar to [9,15] using the equations of motion for the grains with Hertzian contact [1]. The gravitational precompression in the vertically oriented chains was taken into account in the numerical analysis although it has a weak effect at the investigated pulse amplitudes. The effects of dissipation were not included in the calculations and will be addressed in the future.

In the case of the granular protector with a single PTFE central section, the trapping of the incident solitary pulse in the softer region is clearly evident in experiments [Fig. 1(b)] and qualitatively matched the numerical calculations. The experimental data clearly demonstrate that the incident solitary pulse (~ 40 μs long and 8 N in amplitude) is quickly transformed by the PTFE portion of the chain to a much longer signal and it is decomposed into a train of pulses arriving at the wall.

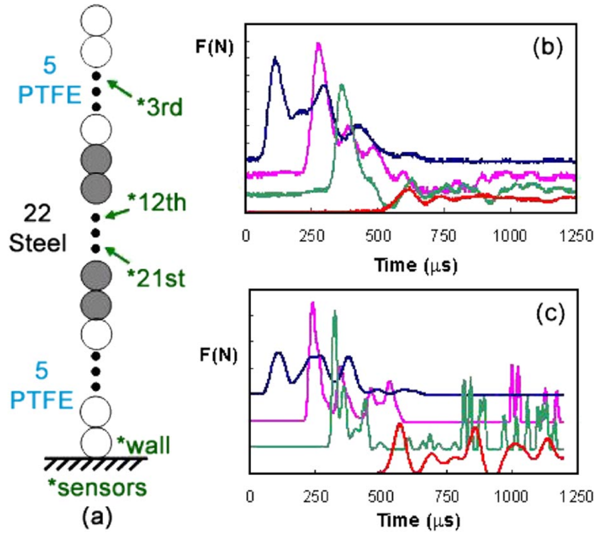

FIG. 2 (color online). Trapping of pulses in the granular protector with a single stainless steel central section. The striker was an Al_2O_3 cylinder of 0.47 g with an impact velocity of 0.44 m/s. (a) Schematic diagram of the experimental setup with indicated sensors. (b) Experimental data. The *y*-axes scale for all curves is 0.2 N per division. (c) Numerical data corresponding to (b). The *y*-axes scale is 1 N per division.

The processes of impulse transformation and confinement, corresponding to the arrangement represented in our Fig. 1(a) (steel-PTFE-steel), are similar to the one presented in [3] (see Fig. 3 there). Specifically, we observed (i) a complete transmission of the energy of the incident solitary wave into the PTFE section without any wave reflection to the steel section (see also [5]), (ii) a significant reflected pulse propagating back into the PTFE section when the incident pulse arrives from the PTFE side of the interface, and (iii) the disintegration of the transmitted impulse into a train of solitary waves.

The solitary wave speed in the steel section of the chain is 357 m/s. The experimental data [Fig. 1(b)] show that the signal speed decreases to 137.4 m/s when the pulse passes through the first interface. This decrease can be attributed to the drastically lower elastic modulus of PTFE (1.46 GPa) compared to steel (193 GPa), which enables the pulses to remain mostly trapped in the softer section of the chain for a relatively long time ‘‘bouncing’’ back and forth between the two interfaces releasing the energy of the impact in both directions very slowly.

The first and largest impulse reaching the wall in Fig. 1(b) has an experimentally measured amplitude significantly smaller (about 5 times) than the one measured in independent experiments in a uniform steel chain under identical impact conditions and the same number of particles. In the numerical calculations the reduction is also very significant being 3 times smaller (amplitude 6.7 N) than the amplitude at the wall (~ 20 N) in a uniform stainless steel chain of beads. The difference between the

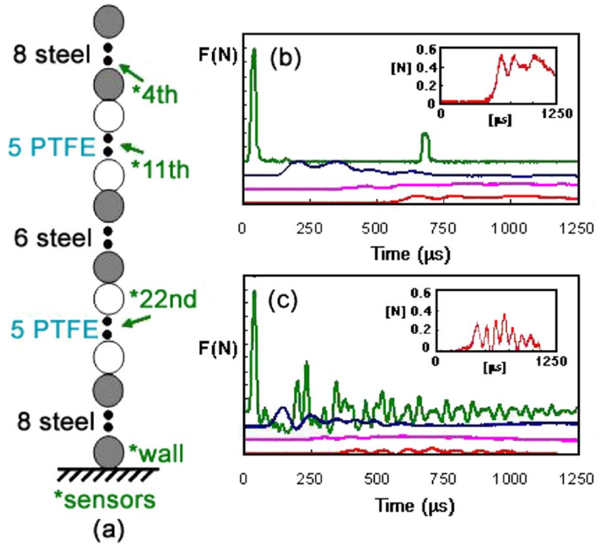

FIG. 3 (color online). Pulse trapping in the composite granular protector with two PTFE sections without and with additional precompresion. (a) Schematic diagram of experimental setup with indicated sensors. (b) Only gravitationally loaded system impacted with an Al_2O_3 striker (0.47 g) at 0.44 m/s. (c) Magnetically precompressed system; all other conditions as in (b). The y-axes scale is 1 N per division. Insets in (b) and (c) show the pulse behavior at the wall. Note the significantly different impulse shape arriving at the wall in (b) and (c). The strong incident impulse (first curve) disintegrates into a very weak series of pulses delivered over a much longer period of time (bottom curve).

experimental data and numerical results is most likely due to dissipation not being included in the numerical calculation, which underestimates the total extent of signal amplitude reduction. It also demonstrates that the dissipation present in the experiments can significantly enhance the protection against incident solitary waves. The trapped pulses reflected from the bottom of the soft central section have an amplitude comparable to the incoming pulses in the PTFE section, demonstrating that a significant amount of the total energy remains confined in the softer central portion of the chain, slowly leaking out only a small amount at each rebound (~28% after the first rebound).

The performance of the granular protector with a single PTFE central section against shock-wave-type loading is shown in Fig. 1(c). To the best of our knowledge its trapping in a granular container was not investigated before theoretically or experimentally, though shocklike loading is very important in practical applications. A shock wave is a qualitatively different type of pulse in comparison with a solitary wave. It is usually characterized by a longer duration which may affect the reflection and transmission at the interfaces. The results of numerical calculations for both types of incident waves (solitary and shock) showed similar tendencies in the impulse behavior which qualitatively agreed with the experimental results.

To compare this particle's arrangement to one proposed in [4] we exchanged the particle's position as described in Fig. 2(a). This new arrangement may be qualitatively compared to the design of one half of the granular container presented in the Fig. 2(c) of [4]. It is evident from the numerical calculations that this arrangement dramatically improved the protection of the wall, reducing the pulse amplitude from 6.7 N observed in the setup of Fig. 1(a) down to ~2 N in Fig. 2(c). A similar trend is observed in experiments where the amplitude of the signal reaching the wall drops from ~1 N in Fig. 1(b) to ~0.2 N in Fig. 2(b).

To investigate the influence of the particle arrangement in our system on the protection efficiency, we reorganized the PTFE beads as shown in Fig. 3(a) increasing the number of interfaces. This geometry resulted in a much better protection of the wall in comparison to the first case studied [compare Fig. 3(b) with Fig. 1(b)] by more efficiently trapping most of the incoming pulse and releasing its energy more slowly. In this case the amplitude of the force calculated numerically at the wall was 3.4 times less (2.4 in experiments) than the one detected in the granular protector with a single PTFE section and ~10 times less than the one observed in an all-steel chain (not shown). The discrepancy between the numerical and experimental case is probably due to the enhanced effects of dissipation at higher signal amplitudes. However, there exists a qualitative agreement of the wave behavior in experiments and numerical calculation for solitary-type loading.

In this setup, the first (uppermost) PTFE section works very efficiently trapping a larger amplitude of the pulse and transforming the 40 μs long incoming solitary pulse (from the steel section) into a much longer and delayed train of signals with an overall duration over 1000 μs. Numerical calculations of the energy contained in the PTFE sections confirmed the higher efficiency of the system: the granular protector with two PTFE sections traps most of the potential energy for a longer time when compared to the single PTFE section and achieves equal wall protection efficiency when compared to the setup presented in Fig. 2(a).

It was previously reported that the wave behavior and the reflection from the interface of two strongly nonlinear systems is strongly affected by an initial precompression causing the phenomenon of "anomalous reflection" of a compression solitary wave [5]. This is because the anticipated combination of pulses contains a solitarylike reflected rarefaction pulse which is not supported by the equations of motion as a stationary wave [1]. This rarefaction pulse, formed very close to the interface, quickly disintegrates into a complex pattern of waves.

To explore the influence of the precompression we tested the more efficient granular protector with two PTFE sections [Fig 3(a)] under a magnetically induced precompression. This resulted in an evident increase of the speed of the signal and in the creation of an anomalous reflected wave [5] on the first steel sensor (uppermost curve) followed by a series of reflected pulses [compare Figs. 3(b) and 3(c)]. The introduction of the preload significantly reduced the force impulse acting on the wall, facilitating the splitting of the signal into a train of low-amplitude waves [see insets of Figs. 3(b) and 3(c)].

The physical explanation for such an increase in the pulse confinement in the softer region of the chain is related to the self assembly of gaps at the interfaces causing a complex ‘‘rattling’’ among the interfacial particles combined with the reflection of the pulse from the interfaces of the soft and rigid regions. These gaps allow the two softer regions of the chain to keep the energy trapped longer, therefore enhancing the protection of the wall. Moreover when the signal propagates through the first interface, a ‘‘fracture wave’’ is formed and propagates back into the stainless steel chain. The presence of these open gaps is counterintuitively enhanced by the static precompression and is responsible for the introduction of a new time scale in the system as well as the formation of an anomalous reflected wave at the interface under precompression [top curve of Fig. 3(c)]. The total energy trapped in the softer sections remains almost constant within the investigated time. Furthermore, the precompressive force transforms the pulse arriving at the wall in a series of well separated pulses, delaying the total momentum reaching the bottom wall. This behavior is very useful as a mean to protect an object from incoming impacts by providing longer distances of pulse traveling within the protector region, thus additionally causing the impact to lose its energy due to dissipation.

The granular protector in Fig. 3(a) was also tested for the trapping of shock pulses, generated by using an Al_2O_3 rod (63 g) as a striker. The incident, oscillatory, fast-ramping shock was dramatically transformed into a long, slowly increasing series of pulses at the wall. This trapped and transformed pulse is likely to be much less damaging to the protected object (the end wall in these experiments). Results of the numerical calculations indicated a similar trend as in the experiments. The data demonstrate that under shock-type loading the softer sections of the chain do not appear to trap energy, thus acting only as pulse transformers, as opposed to the energy trapping of incident solitary waves.

Calculations were also performed for a chain composed of one-by-one alternating stainless steel and PTFE beads. In this case the chain responded as a homogenized ‘‘two-particle system’’ [1] without the creation of reflected pulses, thus drastically reducing the protection.

In conclusion, we demonstrated experimentally and numerically the efficiency of solitonlike and shocklike pulse trapping and disintegration in a composite granular protector and proved that its efficiency depends on the particle’s arrangements. The introduction of a magnetically induced precompression divided the signal reaching the wall into a series of subdivided pulses. The shock-disintegrating principles demonstrated here can be utilized for practical three-dimensional composite structures used for protection against explosive and impact pulses.

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