Dynamic behavior of geometrically complex hybrid composite samples in a Split-Hopkinson Pressure Bar system

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Abstract. The interfaces between layered materials play an important role for the overall mechanical behavior of hybrid composites, particularly during dynamic loading. Moreover, in complex-shaped composites, interfacial failure is strongly affected by the geometry and size of these contact interfaces. As preliminary work for the design of a novel sample geometry that allows to analyze wave reflection phenomena at the interfaces of such materials, a series of experiments using a Split-Hopkinson Pressure Bar technique was performed on five different sample geometries made of a monomaterial steel. A complementary explicit finite element model of the Split-Hopkinson Pressure Bar system was developed and the same sample geometries were studied numerically. The simulated input, reflected and transmitted elastic wave pulses were analyzed for the different sample geometries and were found to agree well with the experimental results. Additional simulations using different composite layers of steel and aluminum (with the same sample geometries) were performed to investigate the effect of material variation on the propagated wave pulses. The numerical results show that the reflected and transmitted wave pulses systematically depend on the sample geometry, and that elastic wave pulse propagation is affected by the properties of individual material layers.

1. Introduction

Hybrid composite structures can be built of different macro-scale layers to combine the beneficial properties of single components, e.g., strength, stiffness, fatigue or corrosion resistance [1, 2]. The contact interfaces of the joined materials play a key role in determining the mechanical behavior of such composites, especially at high strain rates [3, 4]. The interfaces are also important in composite structures with complex shapes, and a detailed experimental characterization is often needed to fully understand their mechanical behavior [5]. The present study is motivated by a need for novel, modified sample geometries that are optimized with respect to homogeneous stress distributions at hybrid interfaces, where wave pulse propagation and reflection typically produce complex stress gradients in conventional samples. Sample preparation of such composite materials, particularly with a reproducible orientation of the interfaces, and the corresponding experimental work, can be quite difficult and costly. Numerical simulations, in contrast, provide a novel tool at reduced costs. They moreover reduce the complexity of mechanical testing and they allow analyzing more details (like local stress and strain distributions) during dynamic testing.
In this paper, the Split-Hopkinson Pressure Bar (SHPB) technique is used to experimentally determine the dynamic behavior of several complex sample geometries under dynamic compressive loading (which produces a shear-dominated deformation of the interfaces that are oriented parallel to the macroscopic loading direction). The SHPB system allows determining the deformation behavior of materials at strain rates from $10^2$ to $10^4 \text{s}^{-1}$. A careful design of this system and high frequency signal acquisition are required to evaluate and analyze the resulting material behavior at these high strain rates [6]. First, a series of experiments is performed with different sample geometries made of monomaterial steel. To complement the experimental studies, the Finite Element Method (FEM) is employed to explicitly simulate the SHPB experiment. The different sample geometries are simulated and the resulting SHPB signals are directly compared to those from the experiments. Finally, the same sample geometries are simulated considering different composite layers of steel and aluminum to determine the effect of both the geometry and of material variations on elastic wave pulse propagation.

2. Experimental and numerical methods
The SHPB system was used to experimentally analyze geometry effects on the dynamic behavior of samples with different, complex shapes. To perform systematic mechanical tests, five different sample geometries made of uniform monomaterial steel were prepared. Figure 1 presents the experimental set-up of the SHPB system (I), and the different sample geometries placed and tested in this set-up (II). The physical mechanism used in SHPB testing is the propagation of a stress wave pulse along a series of long, thin bars. The setup consists of a gas launcher and four bars including the striker, incident and transmitter bars beside a shock absorber bar at the end. The striker bar is accelerated to a pre-defined velocity with the help of the gas launcher (which is charged by a pressurized gas) to hit the incident bar and thus to create an elastic stress pulse. The stress pulse then propagates at the material’s speed of sound through the incident bar. When it meets the sample (placed between the incident and transmitter bars; highlighted by a black circle in figure 1-I), part of the pulse is reflected back to the incident bar, due to a change in cross section and material. In fact, whenever an elastic wave encounters interfaces or changes of the geometrical boundary conditions, partial wave reflection can occur – this also affects the stress state at internal material interfaces [7]. The other part of the signal is passed on through the sample and to the transmitter bar (there is again some reflection at the interface between sample and transmitter bar) and is finally stopped at the shock absorber. In the experimental setup used here, two additional protectors (i.e., thin plates of the same material) are placed at both sides of the sample to prevent damage at the end and front faces of the incident and at transmitter bars. A measurement of the propagated wave pulses, and therefore an analysis of the mechanical response (in terms of force and uniaxial displacement as a function of time) of the material sample, is possible by means of the carefully designed strain gauges, marked using four red arrows in figure 1-I. Not shown is a pulse shaper that is fixed between the striker and incident bars in the experimental SHPB setup, with the aim to reduce superimposed wave pulse oscillations during dynamic testing. Further details on the experimental setup and on the effect of the pulse shaper are, for instance, given in reference [8].

The sample geometries studied here were designed to ultimately serve for mechanical testing of hybrid composite samples consisting of different layers of materials. To study the effect of the unconventional geometries on wave propagation, we first experimentally considered samples produced uniformly from C45 steel (figure 1-II). The geometries start from a simple cube shape with an edge length of 9 mm (geometry “a”), and are then evolved systematically by cutting the front and end faces of the samples in different ways (geometries “b” to “e”). The rationale behind these geometrical variations is that ultimately, interfaces between different material layers are supposed to be subjected to a predominant shear loading. Shear testing of materials is challenging in general [9], and to achieve this in a composite sample, the interfaces can be oriented parallel to the (macroscopically compressive) loading direction as indicated schematically in figure 1-IIb.
Figure 1. (I) Experimental setup of the SHPB system for dynamic testing at high strain rates up to $10^4 \text{s}^{-1}$. The sample is located between the incident and transmitter bars (black circle); red arrows mark positions of strain gauges. (II) Five different sample geometries (“a” - “e”) made of steel were placed in the SHPB setup in the present study to investigate geometry effects on signal propagation during high strain rate testing.

A complementary, explicit FE model of the SHPB system was developed for careful numerical analysis of wave propagation during SHPB testing of the different sample geometries. The fundamental structure of the model is shown schematically in figure 2. The SHPB model consists of the four bars, which are assigned the same material properties (corresponding to steel: $E = 210 \text{ GPa}$; $\nu = 0.28$) and which only deform elastically throughout the whole experiment. A constant diameter of $D = 16 \text{ mm}$ (similar to the actual experimental setup) was set for all the four bars. The five different sample geometries were positioned between the incident and transmitter bars. The simple elastic-plastic mechanical behavior of the material samples was defined by a piecewise fit of the experimentally obtained hardening curve. All sample geometries were created using linear brick elements (C3D8 type) resulting in a relatively large total number of elements (because of the sharp radii present in some samples) of $35,000 – 46,000$.

Figure 2. Schematic representation of the simulated SHPB setup. The four bars are highlighted using different colors; the velocity applied to the striker bar is denoted as $v$. The strain gauges (SGs) are used to measure the propagating elastic wave pulses during dynamic loading. Different specimen geometries are positioned in the SHPB system to determine geometry effects on the contact interfaces of mono- and composite materials with complex shapes.

In all simulations, the striker bar is accelerated to a predefined velocity ($v = 8 \text{ ms}^{-1}$) to hit the incident bar and thus to create an elastic stress wave pulse. The pulse propagates through the whole length of the SHPB system (in z direction as marked in figure 2) and the corresponding elastic deformation is measured (both in the actual experiments and in our simulations) in four different locations by strain gauges (SGs). The SGs 1 and 4 are mounted in the middle of the incident and transmitter bars, respectively, and SGs 2 and 3 are positioned near the front and end faces of the material sample. Two
protectors were also placed at both sides of the sample, similar to the experimental setup (green in figure 2). The effect of a pulse shaper was neglected during the FE simulations. More details on the simulated SHPB setup, specifically on material parameters and boundary conditions, can be found in reference [10].

Finally, an additional series of simulations was performed to numerically assess the effect of material variations and combinations at both sides of the interfaces (as shown schematically in figure 1-IIb) in hybrid composite samples on wave reflection. The same sample geometries were studied, now consisting of a central layer of the C45 steel and two outer layers of technically pure aluminum (E = 70 GPa, v = 0.34). Similar to the initial simulations, the mechanical response was described by simple fits of the corresponding hardening behavior. We note that the focus of these simulations was on wave propagation as opposed to interface damage mechanisms and, therefore, we did not study interface degradation (which would e.g. require a cohesive zone modeling approach).

3. Results and discussion
The numerical results shown in figure 3 illustrate the initiation of the elastic wave pulse and its propagation through the total length of the SHPB system. The individual bars are separated using black dashed lines. The elastic signal is represented by means of the von Mises stress (σ\text{\text{vm}}) distribution at different time steps (given in milliseconds, ms) of the FE simulations. At the beginning of the simulation, the striker bar hits the incident bar at a known velocity and thus creates an elastic stress pulse between the striker and input bars. The initiated pulse is well presented in figure 3, after 0.27 ms. As expected from the fundamental physics of SHPB testing [8], this wave pulse grows until it has reached a total length equal to double the length of the striker bar, as illustrated after 0.31, and 0.36 ms. The signal is then completely transferred to the incident bar (as presented after 0.46 ms). Once the wave pulse reaches the sample, it encounters a change of boundary conditions (both in terms of sample dimensions and material properties), and therefore a partial reflection of the wave occurs at the specimen’s front face. The other part of the wave pulse runs through the material sample towards the transmitter bar. Additional wave reflection occurs between the end and front faces of the material sample and the transmitter bar, respectively. The presence and superposition of the reflected and transmitted elastic waves are evident in figure 3 after 0.60 ms, where von Mises stress distribution clearly exhibits fluctuations along the different bars of the SHPB system.

![Figure 3](image)

**Figure 3.** The von Mises stress distributions at different time steps (time given in ms on the left) of the FE simulations represent the initiation and propagation of an elastic wave pulse in the SHPB system. The input wave pulse moves through the length of the incident bar, parts of this pulse are reflected at the specimen front and end faces while the other part moves through the transmitter bar.

Figure 4 presents the experimental (left) and simulated (right) elastic wave pulse signals (force as a function of time) for testing of the steel samples. The input and reflected signals were measured using SG1 and the transmitted signal by SG3. A shift in the transmitted signals with time compared to the input signals is directly related to the location of SG3 in the SHPB setup. Although the numerical signals exhibit more pronounced oscillations due to the absence of a pulse shaper, they agree well with
experiment. Note that in contrast to the idealized simulations, the strain rate (or the applied velocity) in the series of experiments is subjected to some variations. Therefore the experimental input signals (i.e., the wave pulses observed during the first 5 to 6 ms) of the five separate tests differ somewhat in terms of the maximum force. The samples were deformed plastically during SHPB experiments and no fracture was observed. Obviously, this is in line with the simple simulation approach used in the present study.

According to figure 4, both the experimentally and numerically obtained reflected and transmitted signals exhibit a systematic change with respect to the sample geometry. Geometry “a” transmits almost the entire input signal. A minor reflection dip occurs at the sample front face because of the local change of boundary conditions (material and dimensions). Compared to geometry “a”, a larger part of the input signals is reflected when testing the other geometries (“b”, “c”, “d” and “e”). This indicates more pronounced wave reflections (and a more pronounced decay of the transmitted signals) at the faces of the samples, the more front and end faces are changed from the initial cube geometry. Additionally, an exact analysis of the resulting reflected and transmitted signals indicates a change in the shape of the reflected signals. It could be seen from figure 4 that, except for the geometry “a” where the tangential angle or slopes of the reflected/transmitted signals are almost the same as that of the input signal, the reflected/transmitted signals of the other geometries exhibit a finite slope with time. This slope is likely related to the increase of cross-sectional area as the elastic wave pulse travels through the length of the material samples “b” to “e”.

In summary, these FE results demonstrate that the different specimen geometries studied here have a distinct effect both on the transmitted and reflected signals. The numerical simulations capture various subtle details of the SHPB experiment (for instance, the overshoot dips and peaks of the reflected signals shortly after 6 and 8 ms, respectively).

Figure 4. Experimental (left) and simulated (right) elastic pulse signals for different sample geometries made of steel (C45). The numerical input, reflected and transmitted signals measured in SGs 1 and 3 are in a good agreement with experimental results. Cross-sectional changes clearly affect wave propagation and reflection: samples “b” to “e” exhibit finite slopes of the reflected and transmitted signals.
The results from the monomaterial simulations, particularly the good agreement with the experiments, encouraged the next series of the FE simulations using different composite layers of C45 steel and Aluminum (Al), figure 5. The same sample geometries “a” to “e” were used for a direct comparison between the signals of monomaterial and hybrid samples. Figure 5 presents the resulting input, reflected and transmitted signals of the five composite samples under dynamic loading. The input signals presented in this figure are exactly the same as those of monomaterial simulations presented in figure 4. The overall profiles of the reflected and transmitted signals exhibit a quite similar shape as those of the monomaterial. In contrast to the monomaterial results, a large part of the input signals is reflected because the material variation introduces new contact interfaces even in the cube-shaped sample (geometry “a”). This also results in a considerable wave reflection and a significant slope of the transmitted and reflected signals for sample geometry “a”.

The effect of the different sample geometries can be rationalized by considering the impact of sudden changes in cross-sectional area (highlighted by dashed lines in figure 5) as the wave pulse propagates through each sample. In sample “b”, two distinct jumps occur – one when the cross-section is suddenly increased by adding the outer Al layers, and the other at the free surface (end face of the sample). In sample geometries “c” and “d”, three sudden changes occur; the additional change is related to the free surface at the end of the central steel layer. These samples clearly exhibit the most pronounced amount of signal reflection. Finally, sample “e” is characterized by a soft transition of cross-sectional area (between the dashed lines) and this explains why a larger part of the signal is transmitted. While, from a fracture mechanics point of view, one would expect the geometry of the front faces of the different samples to affect crack initiation, our numerical results demonstrate that the geometrical design of the end faces of such complex hybrid samples also play a key role in determining wave pulse reflection.

![Composite material (C45/Al)](image)

**Figure 5.** Numerical SHPB signals for the five specimen geometries (“a” – “e”) defined using different layers of steel and aluminum. There clearly is an effect of material variation on the propagated signals because hybrid samples contain additional internal interfaces. The reflected and transmitted signals also indicate a more pronounced, systematic dependence on the sample geometry.
We note in closing that, in geometries “a” and “b” with a constant cross-sectional area at the end faces, the mechanical behavior of steel with a higher yield stress strongly affects the SHPB signal. In geometries “c” and “d”, which consist only of Al at their end faces, the SHPB signal is instead dominated by the mechanical response of the much softer Al. It is likely that a modified stacking order of the different materials would further affect to dynamic signals. Obviously, the response of hybrid samples to dynamic testing also depends on the mechanical behavior of the different materials; the complex interplay between different material combinations and geometries warrants further experimental and numerical studies.

4. Summary
The Split-Hopkinson Pressure Bar system was used to study geometry and material effects on hybrid composite materials under dynamic loading. Experiments were performed on monomaterial C45 steel samples with different complex shapes. Complementary Finite Element simulations were performed both on monomaterial samples and on virtual samples consisting different layers of C45 steel and pure aluminum. The experimental and numerical measurements in the Split-Hopkinson Pressure Bar setup for both monomaterial and composite samples with complex geometries indicate a systematic influence of sample geometry and material combination on the reflected and transmitted signals. Free surfaces, changes of cross-sectional area, and internal interfaces between different material layers contribute to varying degrees to partial elastic wave pulse reflection. Particularly in hybrid composites made of different material layers, a substantial part of the input signal is reflected at the interfaces. The overall shape of the reflected signals, and likely internal stress and strain states in the different samples, thus depend on the material combination and on individual specimen geometry.

5. References
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