ELECTRO-MECHANICAL TEST RIGS FOR ANALYSING IMPACT INDUCED WAVE PROPAGATION IN COMPOSITE MATERIALS

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Abstract

Experimental approaches for the investigation of the highly dynamic material and failure characteristics of fibre reinforced materials with special focus on the thickness direction are presented. Two different test rig setups with three different impact scenarios and impact generating methods have been developed to induce elastic waves in a controlled manner with focus on high variability, accuracy and reproducibility. A novel ultra thick composite specimen design (up to 1800 single plies) is used to analyse wave propagation characteristics. The different test rig setups are discussed and compared. Furthermore numerical approaches for designing and analysing the test rig setup on the one hand and investigating the mechanical wave propagation and failure mechanisms in the specimen are explained. Selected results are presented.

1 Introduction

Most impact scenarios involving structural components made of laminated composite materials cause significant loading proportions in the materials thickness direction. The subsequently induced mechanical compression wave propagates through the composite material and may lead to structural failure. Such layered structures typically exhibit a significantly lower tensile strength in thickness direction in comparison to the respective compression strength. The compressive waves introduced at the impact location return as tensile waves due to wave reflection at free boundaries and may subsequently initiate delamination failure. [1]

For the understanding of the occurring phenomena and validation of numerical modelling approaches, the elastic wave propagation characteristics need to be experimentally assessed. A commonly used approach for high strain rate material characterisation is the split Hopkinson bar setup [2]. However, for composite materials this setup can not always reliably be used due to the usually required small specimen sizes. The presented novel test rigs extend the highly dynamic testing possibilities for composite materials. In this investigations, long cylindrical specimens with special focus on the material thickness direction are used, where a coplanar impact contact of an impactor and the specimen results in an idealized 1D-wave propagation of the induced impulse through the specimen.

2 Specimen manufacturing and instrumentation

The manufacturing process of the cylindrical through thickness specimens is shown in Figure 1 a. The x-y plane denotes the in-plane fibre reinforced cross section of the specimen and the z-direction represents the stacking or the through thickness direction respectively. This setup can be used for either thermoplastic (Figure 1 b top – glass fibre reinforced multi layered knitted fabric) or thermoset materials (Figure 1 b bottom – unidirectional carbon fibre prepreg). With this manufacturing technique ultra thick stacked laminate specimens of up to 230 mm length, 40 mm diameter and up to 1800 single plies can be tested. To properly record the impact induced mechanical waves in the specimen, two interchangeable and combinable instrumentation techniques are used: on the one hand surface mounted strain gauges (sg) - Figure 1 b top - and and on the other hand integrated piezo based sensing elements (piezo) - Figure 1 b bottom. To assess the quality and especially the planarity of the impact, strain gauges are positioned circumferentially. Also, sg are positioned axially for wave propagation analysis. The data aquisation is realized using up to 16 indepent sampling channels with up to 60 MHz sampling rate.

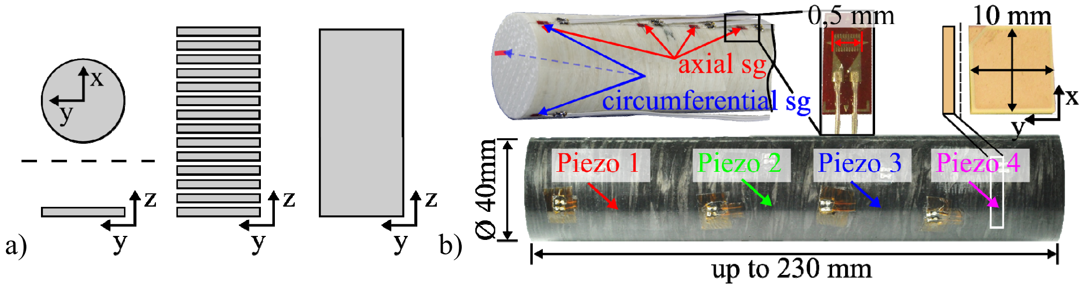


Figure 1. a) Schematic manufacturing process of the new designed cylindrical shaped specimen for high dynamic material characterisation in composite thickness direction; x-y plane: cross section with in-plane fibre reinforcement; y-z plane: stacking/ thickness direction
b) Exemplary instrumented specimens with surface mounted strain gauges (sg) and integrated piezo based sensing elements

3 Test rig concepts

The following major requirements for the experimental investigations of wave propagation analysis have to be fulfilled when designing new test rigs:

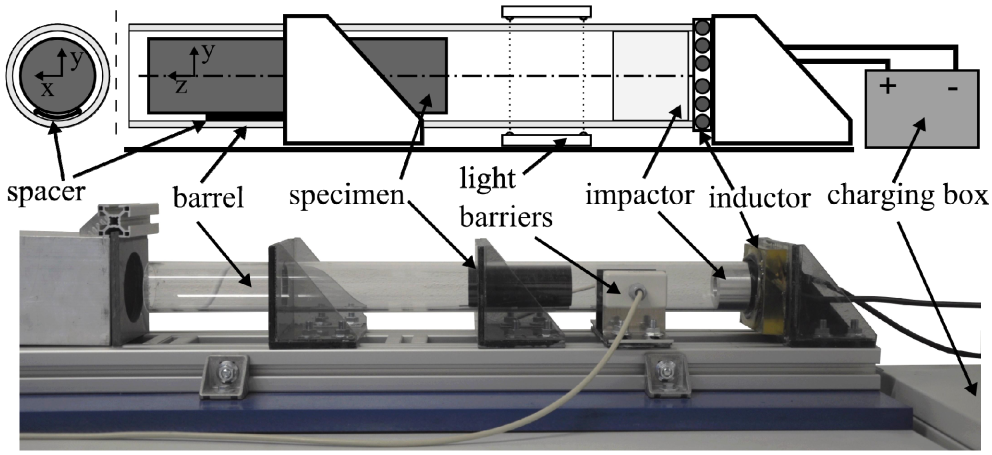
- High accuracy, reproducibility and simple adjustments of impact energy or impact velocity
- Easy and save to operate (no special permissons, e.g. when using explosives)
- Easy, cost effective modification and adaptation options
- Ideally small spacing demands and mobility of the system

Two different test rig setups with three possible configurations have been developed. The basic working principle and major components of the setups are illustrated in Figure 2 and Figure 4.

3.1 Impactor impulse based single impact setup (ISI)

The impactor acceleration is based on two repelling magnetic fields, caused by an electric inductor and the corresponding electromagnetic induced eddy-currents in the impactor, see Figure 2. For this purpose, a charging box, consisting of a high voltage and high capacity capacitor bank is used to form an electrical resonant circuit with the inductor. By varying the capacitor bank voltage, the impactor velocity and therefore the induced impact energy can be precicely and repeatably adjusted.
The tests are carried out under vacuum conditions to eliminate significant slowing-down effects by air drag due to the high initial acceleration. Additionally, this impact setup allows a very flexible and compact device design as well as highly accurate and repeatable impact parameter settings. The aim of a coaxial impact with the cylindrical impact partners is achieved by guiding the impactor in the barrel. A coplanar impact contact results in an idealised 1D-wave propagation of the induced impulse in the specimen. The impactor length affects the impulse length, whereas the amplitude is governed by the impact velocity. Changing the impactor material by using different paramagnetic materials, putting additional impactor attachments of different material in front of the main impactor or realising geometric changes, e.g. circumferentially grooves [3] on the impactor, results in different resulting pulse shapes.

a)



b)

Figure 2. a) Schematic and b) realized experimental setup with its test rig components for the investigation of impact induced wave propagation in composite materials using impactor impulse based single impact setup (ISI)

3.2 Selected results of the impactor impulse based single impact setup (ISI)

In Figure 3, exemplary normalized strain over time plots of the specimen and instrumention, as shown in Figure 2 b top, are presented. The surface mounted circumferientially strain gauges (three, shifted by 120°), and four equally spaced in the axial direction are used to record the induced mechanical waves, their propagation as well as the relaxation behaviour of the material. Furthermore one can derive the strain rate $\dot{\varepsilon}$, the wave propagation speed c as well as the quality and planarity of the impact event by evaluating the circumferental sg signals, denoted by d.
By varying the impactor velocity it is easy to switch from pure elatic induced waves to more damaging and failure relevant specimen loads.

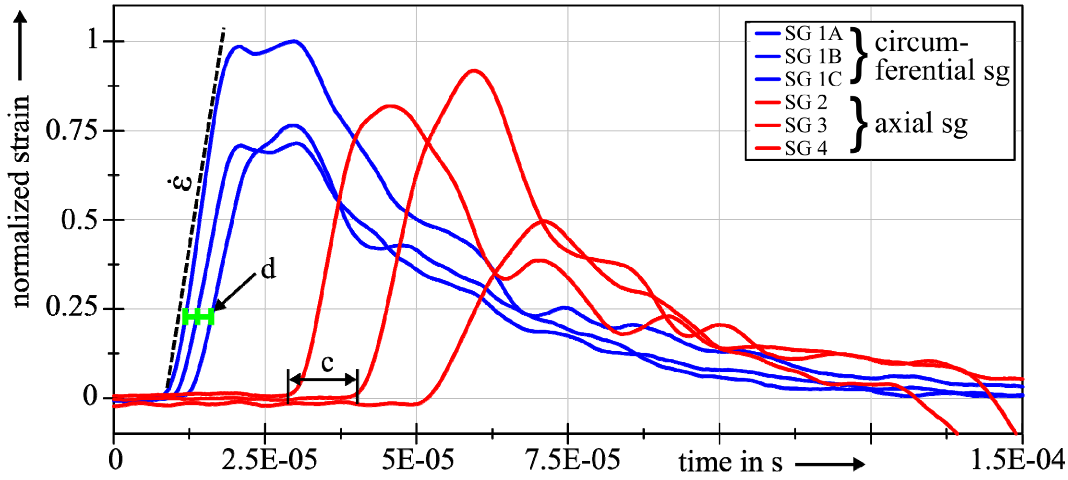


Figure 3. Exemplary test results of the impactor impulse based single impact setup (ISI); normalized strain over time curves recorded with circumferientially (120° shifted) and axially (equally spaced) surface mounted strain gauges (sg); $\dot{\varepsilon}$, c and d denote the derived strain rate, the wave propagation speed and the timing difference of the circumferientially sg

3.3 Piezo impulse based single impact setup (PSI):

In contrast to the ISI setup, the induced wave is not generated by impact of a freely flying projectile, but rather based on a piezo actuator excitation mechanism, see Figure 4. The piezo actuator is capable of reproducing very high accelerations needed to replicate the high strain rates caused by impact events. The contact surfaces of the cylindrical specimen is in direct contact with the piezo actuator mechanismen.

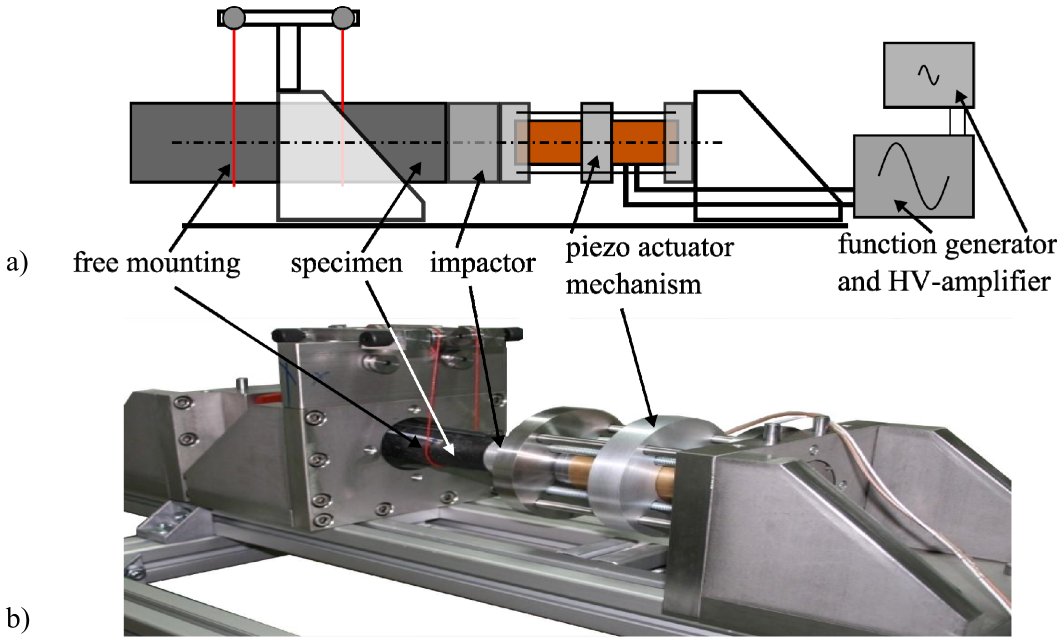


Figure 4. a) Schematic and b) realized experimental setup with its test rig components for the investigation of impact induced wave propagation in composite materials Piezo impulse based single impact setup (PSI)

With this basic excitation principle it is easy to freely adjust the generated load and displacement behavior of the actuator mechanism by simply choosing from a huge varyity of available piezo actuator stacks of different sizes and actuation capabilities. One can e.g. use one big piezo actuator like shown in Figure 4 or using two or more actors either in serial setup to increase the generated load or in parallel to switch from a coplanar to a tilted impact [4]. The single impact impulse is generated by sending a pre-defined pulse shape via a funtction generator through a high voltage amplifier directly to the piezo actuator. By adjusting the form, the amplitude and timing (pulse width) of the initial pulse within the function generator, the loading conditions of the specimen can be easily adapted. Additional pulse shaping can be realizedby replacing or adding different impactor materials or geometrically changed impactor shapes. Furthermore no vacuum is required.

3.4 Selected results of the piezo impulse based single impact setup (PSI)

In Figure 5 exemplary normalized strain over time curves of the specimen and instrumention design, shown in Figure 2 b bottom, are shown to illustrate the potential of the given PSI test rig setup. In analogy to Figure 3 the induced impulse form, the resulting strain rate $\dot{\boldsymbol{\varepsilon}}$, damping behaviour and wave propagation characteristics (c denotes material speed of sound) of different loading intensities can be analysed. Here, a different strain measuring technique is used. The developed thick stacked composite specimen enables a novel measurement approach for 1D longitudinal strain waves. Instead of surface mounted strain gauges, integrated sensing elements using the piezo electric effect are used. Four of these sensing elements are placed axially spaced wihin the cross section of the specimen. These piezo sensors have a very high sensistivity and are eable to detect even smallest amount of strain waves in the thickness direction. In combination with standard strain gauges it is now possible to enhance the data quality and ensure that not only surface waves are excited.

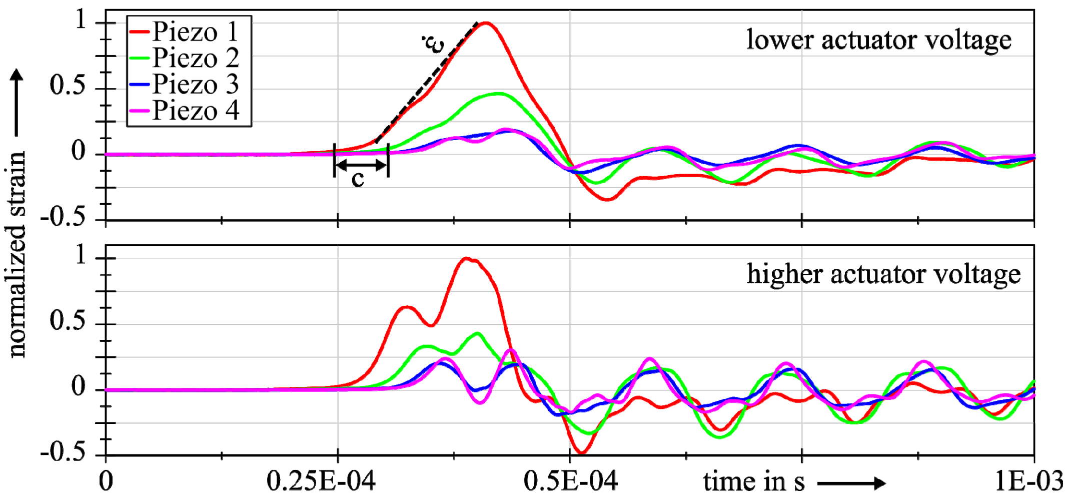


Figure 5. Exemplary test results of the piezo impulse based single impact setup (PSI); normalized strain over time curves recorded with integrated piezo based sensing elements with different loading intensities; $\dot{\boldsymbol{\varepsilon}}$ and c and the derived strain rate and wave propagation speed

3.5 Piezo impulse based multiple impact setup (PMI)

Based on the single impulse method of the PSI setup, the impact setup using piezo actuator stacks allows automated repetitive introduction of impact impulses of different amplitudes as well as pulse length and impulse frequency. This can be achieved by simply adding repetitive output pulse with a programmable function generator or by using a more complex, interactive PC coupled control and regulation interaction method with e.g. Matlab or LabView connection. A special modification at the impact opposing end is added to reposition the specimen and guarantee that every single impact event has the same initial conditions.

3.6 Selected results of the piezo impulse based multiple impact setup (PMI)

With this experimental repetitive impact method it is now possible to rebuild real world multiple impact szenarios like hail and stone as well as multiple foreign object impacts with high precision and determined repeatability. The propapbly changing material, degradation and failure behaviour under repetitive high strain rate loading conditions can now be easily and effectively investigated. This is very important for structural components using fibre reinforced composite materials e.g. airplane parts, jet engine fan blade components, etc., which are placed mostly unprotected on the outer surface. Figure 6 illustrates the recorded strain data of a multi impact based experiment using the PMI technique with ten separated impulses, delayed with 1 second.

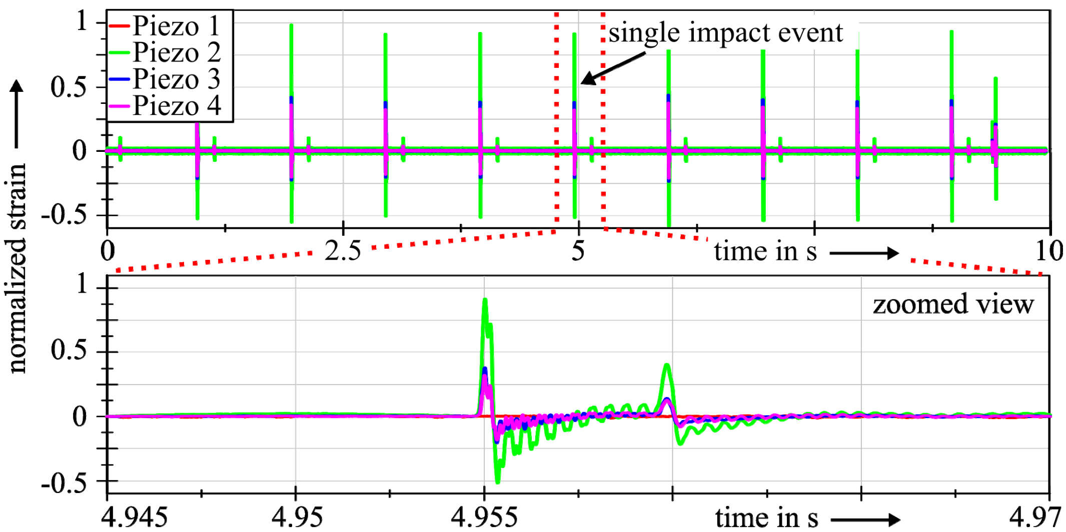


Figure 6. Exemplary test results of the piezo impulse based multiple impact setup (PMI); normalized strain over time curves recorded with integrated piezo based sensing elements; top: ten 1s delayed induced impact impulses, bottom: detailed view on one single impact event

4 Numerical methods/ approach

Due to the complexity of the excitation mechanisms either the electromagnetic projectile acceleration using eddy currents or the piezo actuator based impact mechanism, the usage of standard and multiphysic finite element approaches is used to analyse, understand and optimise the testing setup. Additionally, wave propagation, damage and failure behaviour under high strain rates in very thick composite materials can be evaluated. The direct comparison of the experimental data and the numerical results leads to a validated simulation strategy. Especially for the designing process of more impact resistant structural composite parts, such strategies can be used to generate a more in-depth understanding of the structural response. In Figure 7 the simulation methodology for the ISI setup is shown. Initially, a pre-analysis is performed using a simplified 2D FEMM (Finite Element Method Magnetics) model to estimate the resulting magnetic field and acting forces between an inductor and an impactor for a given electrical resonant circuit, shown in Figure 7 a. For more detailed investigations a coupled electromagnetic-mechanic explicit finite element (FEM) LS-DYNA model of the acceleration mechanism and the structural response of the specimen after the impact is used. Within this model different inductor-impactor configurations with their corresponding electromagnetic behaviour as well as the impact event, the induced compression wave and propagation phenomena and even the damage and failure behaviour of the composite can be analysed within a single simulation.

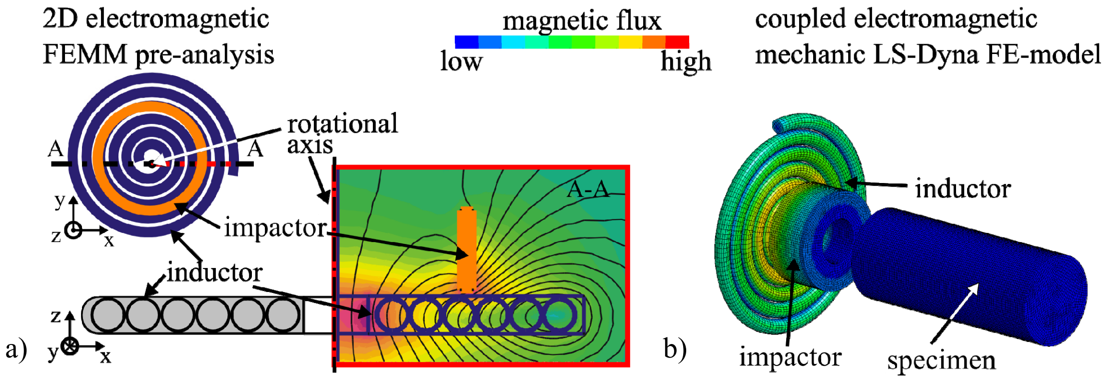


Figure 7. ISI simulation strategies: a) simplified 2D FEMM (Finite Element Method Magnetics) model for magnetic field and resulting force estimation for a given inductor-impactor configuration, b) coupled electromagnetic mechanic explicit LS-DYNA model for more detailed and complex numerical analysis

For the numerical PSI and PMI investigations an explicit LS-DYNA model (Figure 8) is used to analyse the complex interaction of propagating mechanical waves with the surrounding elements, e.g. actor clamping and holding devices, with the specimen. Therefore design limitations and possible design faults of the actuator mechanismens can be identified and eliminated.

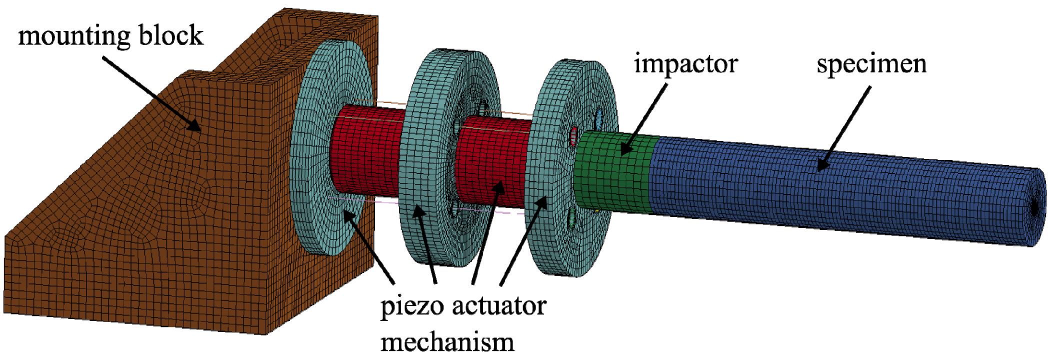


Figure 8. PSI and PMI explicit LS-DYNA model for analysing the complex mechanical wave propagation and wave interaction between the test rig components

5 Conclusions

The presented experimental and numerical methodologies for investigating the impact induced wave propagation within novel very thick composite material specimen in thickness direction can be used to achieve a more in-depth understanding of the deformation, damage and failure behaviour under high strain rates. However, each concept has its own advantages and limitations, they have a high accuracy, reproducibility and practicability in common.

The ISI test rig setup with its few components and simple and cost effective design concept provides high impact energies but requires a more demanding specimen positioning, additional vacuum within the barrel and lacks the possibility of high frequent multiple impact testing.

In the PSI and PMI setups, the necessity of a vacuum assisted experimental setup is eliminated. Also, the possibility of very easy pulse shaping is given by simply programming the wave inducing piezo actuator with arbitrary voltage curves and modifying the impactor shape. However, the complex wave propagation interactions between the different parts of the test rig and the specimen require a more complex designing process to get the necessary impulse shapes within the specimen. Furthermore to reach the same impact energies like in the ISI setup, costly high voltage amplifiers and piezo actuators are required.

Acknowledgments

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