Application of digital image correlation and high speed photography to determine the fiber failure fracture toughness of composites under high rate loading

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Abstract. This work presents the determination of the compressive and tensile crack resistance curves of a unidirectional composite when submitted to dynamic loading. The data reduction couples the concepts of energy release rate, size effect law and R-curve. Both split-Hopkinson bar and quasi-static reference tests with double-edge notched specimens of different sizes are performed. The specimen deformation and in-plane strain vector are determined via digital image correlation, allowing a detailed study of specimen deformation and failure mechanism. In addition, the digital image correlation data is used to evaluate the applicability of the quasi-static fracture theory for the split-Hopkinson bar tests.

Introduction

Automotive and aeronautical composite structures are subjected to dynamic load scenarios (e.g. crash, bird strike). Recently, energy-based damage models, able to predict initiation and evolution of damage, have become popular and are now available for static loading in commercial FE codes. The models require the specification of fracture toughness parameters for the main failure modes to predict damage evolution after the material strength has been reached. However, no test standards exist to measure the static and dynamic fracture toughness for compressive and tensile fiber failure.

In the presented work, the methodology suggested by Catalanotti et al. [1, 2] to measure the crack resistance curves is enhanced to dynamic loading at split-Hopkinson bar setups. As summarized by Jiang & Vecchio [3] various Hopkinson bar configurations have been used for investigating dynamic fracture mechanisms of engineering materials, but little research has been performed to ensure that quasi-static fracture theory is still applicable for the data reduction of the dynamic fracture experiments. In this work, an approach is presented how digital image correlation data can make a contribution to this critical point in the data reduction.

Determination of the crack resistance curves

The methodology presented by Catalanotti et al. [1,2] uses the relations between the energy release rate (ERR), the crack resistance curve and the size-effect law. For determination of the latter, tests with double-edge-notched (DEN) specimens of different sizes are required and the results can be used for the calculation of the corresponding energy release rate curves. Finally, the R-curve is the envelope of the ERR-curves, as illustrated in Fig. 1a. For the quantification of the strain rate effect, tests are performed at an electromechanical testing machine under quasi-static (QS) conditions and at split-Hopkinson bars under high rate loading (HR, strain rate about 100 1/s). For the carbon-epoxy material IM7/8552, an increase of the fracture toughness for fiber compressive and tensile failure mode is found with increasing strain rate, as shown in Fig. 1b for compressive loading. A more detailed description of the experimental work can be found in [4,5].

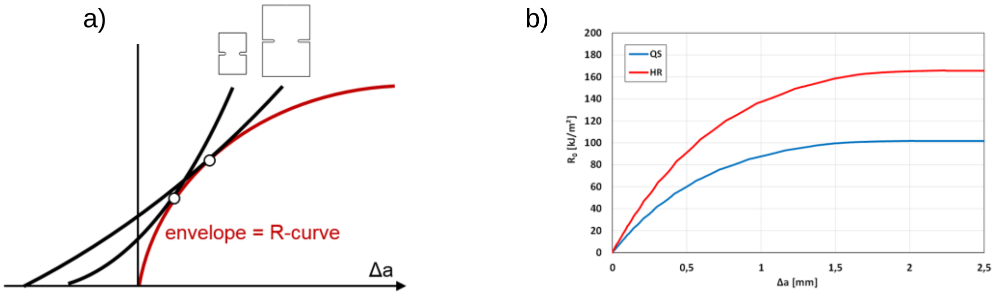

Fig. 1: Schematic illustration of the R-curve calculation methodology (a), R-curve of IM7/8552 for fiber compression failure mode at QS- and HR-loading (b)

Use of digital image correlation

The specimen deformation and in-plane strain vector are determined via digital image correlation, allowing a detailed study of specimen deformation and failure mechanism. In the presented work, the *GOM ARAMIS-4M* system in a 3D configuration was used for the quasi-static measurements and the specimen deformation under high rate loading was monitored by a single *Photron FASTCAM SA-Z*. Fig. 2 shows that failure mode and strain field distribution of the compression specimens have the same characteristic at both loading regimes which is essential to the comparability of the results and determination of the strain rate effect. It can further be seen that the shear strain field shows zero shear strain in the central part of the specimen near the crack tip, indicating pure mode I loading conditions as desired.

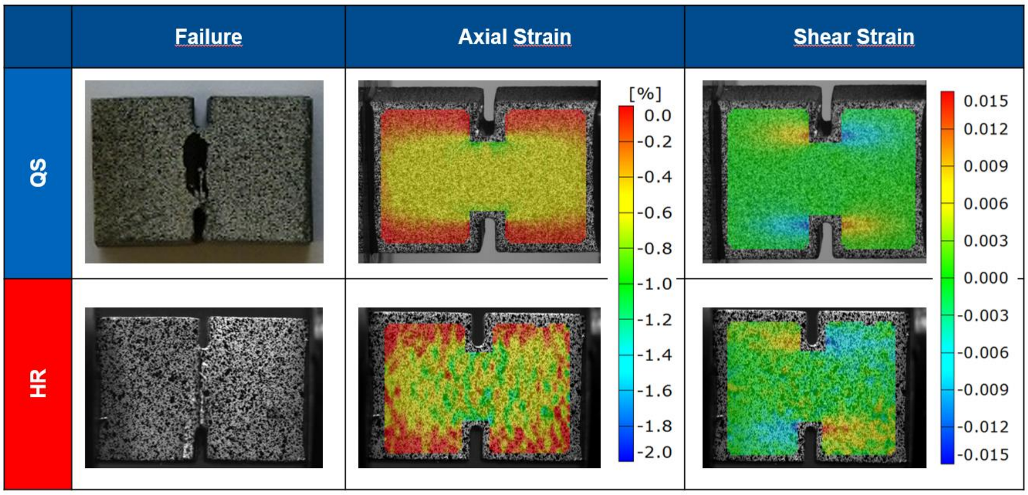

Fig. 2: Failure mode and strain fields under quasi-static (QS) and high rate (HR) loading conditions

In addition, the digital image correlation data are used to evaluate the applicability of the quasi-static fracture theory for the split-Hopkinson bar tests, which if possible results in much simpler data reduction of the dynamic tests. The strain energy and kinetic energy of the specimen are calculated on basis of the 2D displacement field. The comparison of both values shows (Fig. 3) that the kinetic energy at specimen failure is <1% of the strain energy. Inertia effects can therefore be neglected and the quasi-static fracture theory is applicable also for the data reduction of DEN specimens tested at split-Hopkinson Bars.

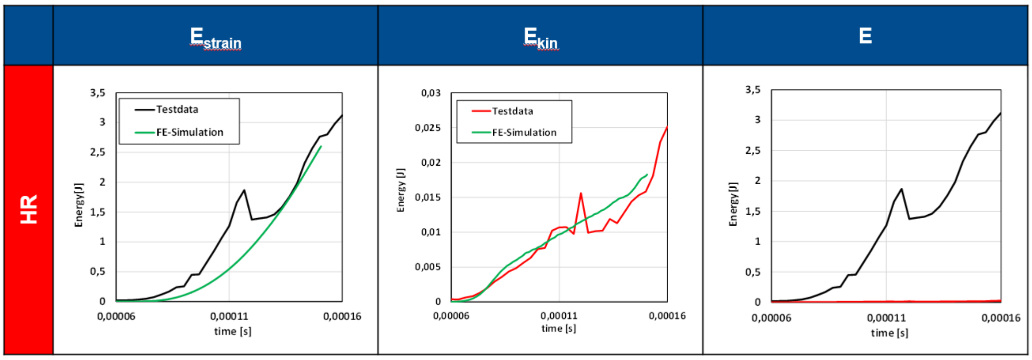

Fig. 3: Strain energy and kinetic energy curves under high rate loading, based on DIC and FE-simulation

Conclusion

The presented work shows that the strain rate effect of the fracture toughness for fiber failure modes of composites can be determined in a reliable way using split-Hopkinson bar setups. The use of DIC contributes significantly to ensure comparability of the results at both investigated strain rate regimes. In addition to the classical stress equilibrium check, DIC can be used to show that quasi-static fracture theory is applicable for the data reduction of the DEN specimens under high rate loading.

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