Polskie Towarzystwo Materiałów Kompozytowych
Polish Society of Composite Materials
Kompozyty 11: 3 (2011) 264-267
KOMPOZYTY
COMPOSITES

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Otrzymano (Received) 25.03.2011

EXPERIMENTAL AND NUMERICAL ANALYSIS OF STRAIN RATE DEPENDENT ON MATERIAL BEHAVIOUR OF GLASS FIBRE REINFORCED POLYPROPYLENE

This paper describes the research work to characterise the strain rate dependent on the deformation and failure behaviour of glass fibre reinforced polypropylene. The experimental and theoretical analysis of the mechanical behaviour under highly dynamic loading is performed within the German DFG research project "Textile reinforced composite components for function integrating multi material design in complex lightweight applications". The investigations are used for the development of novel material models for the strain rate dependent on material behaviour under in-plane and out-off-plane loads. Therefore, highly dynamic tensile and compression tests on textile reinforced composites with a thermoplastic matrix and woven or knitted fabric reinforcement are performed for determination of the strain rate, orientation dependent stiffness, strength characteristics, as well as for identification of the material specific failure and damage behaviour. Within the research work, novel testing methods and devices were developed, which enable a defined loading and accurate strain and damage analysis. Based on the experimental results, approaches for extended material models were developed, which include the strain rate dependent deformation behaviour on the one hand and the fracture mode specific failure behaviour on the other hand.

Keywords: **glass fibre reinforced polypropylene, strain rate, high speed material testing, constitutive modelling**

DOŚWIADCZALNA I NUMERYCZNA ANALIZA ZACHOWANIA SIĘ MATERIAŁU W ZALEŻNOŚCI OD SZYBKOŚCI ODKSZTAŁCENIA DLA POLIPROPYLENU WZMOCNIONEGO WŁÓKNEM SZKLANYM

W artykule przedstawiono badania określające rozmiar deformacji oraz powstałych uszkodzeń w zależności od szybkości odkształcenia polipropylenu wzmacnianego włóknem szklanym. Analiza zarówno eksperymentalna, jak i teoretyczna zachowań mechanicznych badanych materiałów, w zależności od przyłożonego obciążenia dynamicznego, została przeprowadzona w ramach projektu badawczego DFG „Textile-reinforced composite components for function-integrating multi-material design in complex lightweight applications". Badania te mają posłużyć opracowaniu nowych modeli materiałowych opisujących zachowanie materiału obciążonego w płaszczyźnie wzmocnienia, a także w kierunku prostopadłym do ułożenia wzmocnienia w zależności od szybkości jego odkształcenia. Przeprowadzone badania (dynamiczne rozciąganie i ściskanie) termoplastów wzmocnionych tkaninami lub dzianinami zostały wykonywane w celu określenia charakterystyk sztywności i wytrzymałości w zależności od szybkości odkształcenia i orientacji włókien oraz identyfikacji powstałych uszkodzeń w zależności od wykorzystanego rodzaju materiału. W ramach pracy opracowano nowe metody oraz urządzenia badawcze pozwalające na dokładne zdefiniowanie obciążenia oraz analizę odkształceń i uszkodzeń. Na podstawie wyników eksperymentalnych w opracowywanych modelach materiałowych należało uwzględniać nie tylko rozmiar deformacji w zależności od szybkości odkształcenia, ale również rodzaje powstałych przełomów. Opracowane modele zostały następnie wykorzystane w symulacjach numerycznych zjawiska zderzenia w płaszczyźnie wzmocnienia.

Słowa kluczowe: **polipropylen wzmocniony włóknem szklanym, prędkości odkształcenia, dynamiczne badania materiałów, modelowanie konstytutywne**

INTRODUCTION

Fibre reinforced composite materials are well known for their outstanding mechanical properties at a specific low weight which allows engineers to design thin, yet stiff structures without loss of performance. Especially, composite materials with thermoplastic matrix systems are predestined for lightweight crash and impact loaded applications because of their excellent fracture toughness which originate mainly through the formation of a myriad of micro cracks [1, 2]. Despite their many virtues, they show complex deformation and failure behaviour under highly dynamic loads. Therefore, in impact engineering, the response of composite materials to rapidly applied load has to be assessed in order to observe and quantify any rate of dependent behaviour [3]. As a result, new experimental procedures are being devised in order to subject the proposed specimen designs to controlled dynamic loading so as to minimise the difference between the corresponding experiments performed at quasi-static loading rates. Ideally, the difference between the two should be only in the rate at which the load is applied to specimens. Furthermore, existing material laws for fibre reinforced composites have to be extended to depict the anisotropic deformation and the mode related fracture behaviour dependent on the strain rates.

The main objective of this paper is to present improved experimental methods for the characterisation of the strain rate material behaviour of fibre reinforced composites with a thermoplastic matrix. These novel testing methods and devices enable defined loading and accurate strain and damage analysis for in-plane and out-of-plane loading. The developed highly dynamic tensile and compression tests are performed to determine the strain rate and orientation dependent stiffness and strength characteristics and to identify the material specific failure and damage behaviour of fibre reinforced composites with a thermoplastic matrix and woven or knitted fabric reinforcement.

Based on the experimental results, approaches for extended material models were developed, which include strain rate dependent deformation behaviour and fracture mode specific failure behaviour for in- and out-of -plane loads.

EXPERIMENTAL SETUP, AND TESTING CONFIGURATIONS

The baseline of the experimental work in this study is an already existing INSTRON high speed test rig for tension and compression tests up to 20 m/s and 160 kN. In the case of the tension test, the specimen is fixed in the lower grip while the upper grip accelerates to test speed before it closes rapidly (see Fig. 1). The strain rate at which the test area of the specimen is loaded depends on the shape and size of the specimen. Nonetheless, while metallic specimens for high strain rate tests have a simple necked test zone, composite specimens have to be designed depending especially on their fibre architecture and fibre orientation, whereas stress concentrations have to be avoided.

For the performance of high speed in-plane compression tests, a modified test setup was developed on the basis of CELANES equipment. Furthermore, a high speed IOSIPESCU shear test facility was designed. The compression and shear test facilities are both designed in light weight design to reduce oscillation during testing. Furthermore, additional and modified guiding elements were developed to avoid instabilities during the loading of the fixtures which could cause uncontrolled destruction of the specimen or of the facility itself. The designed shear facility is shown in Figure 2.

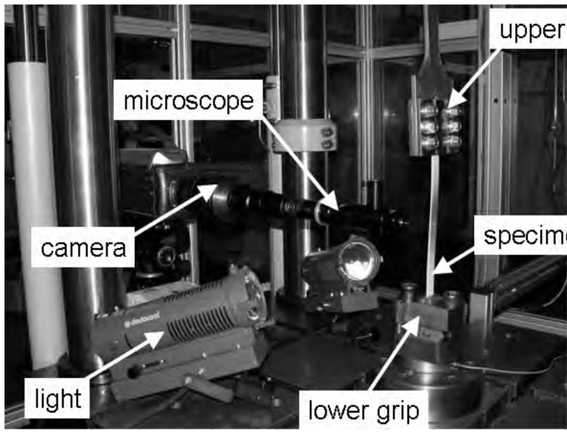

Fig. 1. Experimental test setup for tension tests at high strain rates

Rys. 1. Stanowisko badawcze do badań wytrzymałości na rozciąganie przy dużych szybkościach odkształcenia

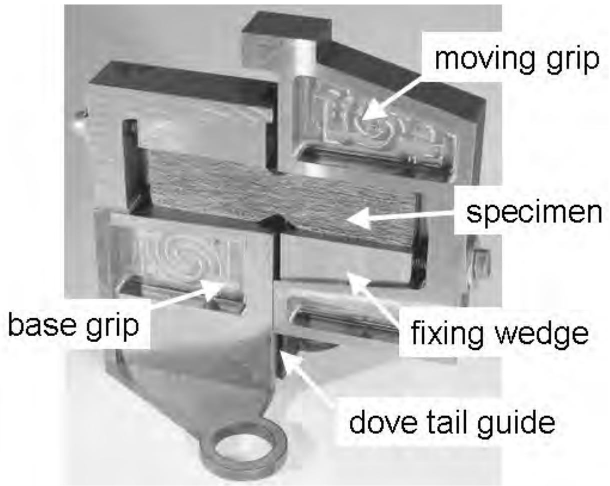

Fig. 2. High dynamic IOSIPESCU shear test facility

Rys. 2. Urządzenie do badania wytrzymałości na ścinanie metodą IOSIPESCU

In addition to the described tension, compression and shear tests for in-plane and out-of-plane loading, additional tension tests on L-beam specimens and high speed bending tests on flat specimens and plates were performed. These tests are documented in [4-7].

To determine the induced strain field at high loading speed, different technologies were employed within the experimental work. Methods which are based on the test rig integrated sensor indicating the position of the upper grip or which are based on laser Doppler methods are strongly influenced through the elasticity and vibration of the loading line. Therefore, the strain at high loading speed was determined using an optical measuring technique applying a high speed camera system in combination with the GOM measuring system ARAMIS. This measuring technique enables accurate measurement of the strain in and transversal to the loading direction.

MATERIALS

Three types of textile reinforcement were investigated. Uni-directional (UD) glass fibre reinforced polypropylene was analysed at first to determine the basic material behaviour depending on the fibre direction. Furthermore, a glass fibre polypropylene composite with a woven and biaxial weft knitted reinforcement was tested. The tested specimens were fabricated in an autoclave or in a high temperature press process using semi finished products made of hybrid yarn. The specimens were cut out of the panels in three different angles, namely 0°, 45°, and 90° with 6 specimens for each testing configuration.

EXPERIMENTAL RESULTS

Among the several factors known to influence strain rate deformation and failure behaviour of composites, fibre stiffness and strengths, matrix toughness, panel thickness, lay-up, fibre arrangement, loading velocity and support conditions are considered to be the most important ones. In the scope of this paper, only the factors related to lay-up, fibre architecture and arrangement were considered. The findings of the experimental work conducted are summarised below.

Tension and compression tests

In-plane tension tests were performed in 0°, 45° and 90° fibre orientation on the above-mentioned composite materials at strain rates up to 120 1/s. Exemplarily, Figure 3 shows the stress strain curves of a bidirectional reinforced glass fibre reinforced polypropylene composite with a knitted textile reinforcement for different strain rates. For all the tested materials and for all the fibre directions, strain rate deformation behaviour was detected. This result corresponds to the phenomenological models that describe strain rate dependent deformation behaviour for isolated glass fibres and for polypropylene. As expected, the influence of the strain rate on deformation is smaller for loading in the fibre direction compared to loading transversal or 45° to the fibre direction. An increase of the strain rate of six orders of magnitude results in an increase of stiffness of about 60% in the fibre direction and about 46 % transversal to the fibre direction.

In the case of strength, strain rate dependency was found for loading in the fibre direction of unidirectional reinforced composites. For an increase of strain rate of six orders of magnitude, an increase of strength of 80% was determined. No influence could be determined for testing UD composites transverse to their fibre direction. This result is at first surprising because it was expected that the polypropylene, which dominates the transversal deformation behaviour and which shows strong dependence of strength on the strain rate, will also influence the inter fibre failure behaviour. In microscopic analysis, inter fibre failures at the interface of the fibre and matrix was found. These failures are typically very brittle and do not depend on the loading speed.

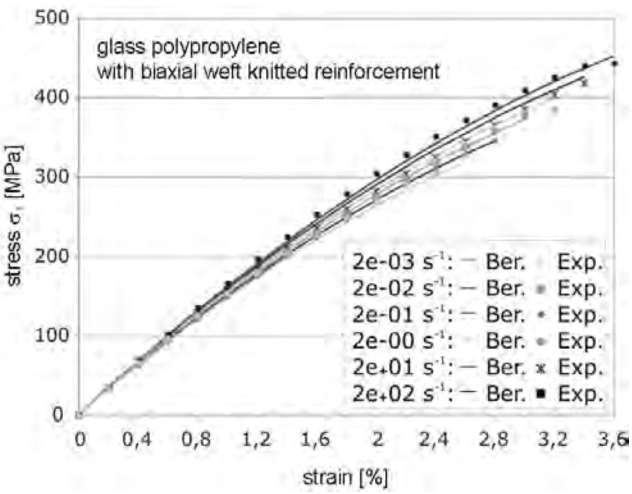

Fig. 3. Stress strain curves of glass polypropylene composite with woven reinforcement

Rys. 3. Krzywa odkształcenie-naprężenia polipropylenu wzmocnionego tkaniną szklaną

For all the specimens with woven and biaxial weft knitted reinforcement, strain rate dependent deformation and failure behaviour were detected for all the loading directions. The specimens with woven reinforcement show an increase of stiffness and strength up to 50%. In the case of knitted reinforcement, the increase is smaller because of the non-crimped fibres (35%).

The out-of-plane tension tests indicate a similar behaviour to that found in the in-plane tests on a UD specimen in unidirectional reinforced composites with a strong influence of strain rate on the deformation behaviour while the failure behaviour is not controlled by the loading speed.

In-plane compression tests were performed on specimens with woven and biaxial weft knitted reinforcement at strain rates up to 200 1/s in 0° and 90° direction. The tests on the specimen with woven reinforcement show that the stiffness and strength increases up to 30% (strength) and 80% (stiffness).

Shear tests

Shear tests were performed in 1-2 and 2-3 plane at strain rates up to 60 1/s. Figure 4 shows exemplar stress strain curves of glass polypropylene composites with woven and biaxial weft knitted reinforcement for the 1-2 and 2-3 plane. In the case of the tests for the 1-2 plane, an increase of stiffness of 75% for an increase of strain rate over 5 orders of magnitude was determined. The strength increases up to 140%. For the 1-3 plane no noticeable increase of stiffness or strength can be detected. The reason for this at first unexpected behaviour can be seen in a very early inter fibre failure that occurs at the interface of the fibre and matrix.

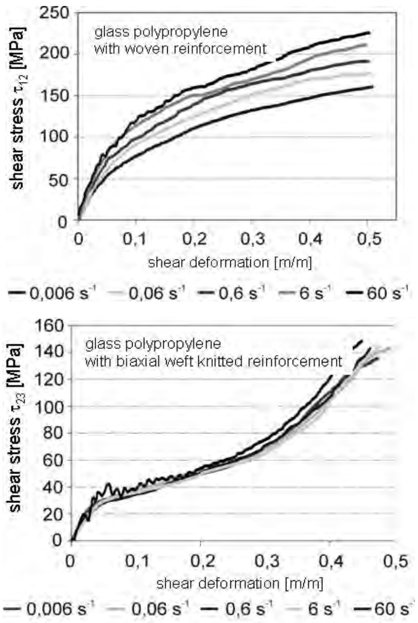

Fig. 4. Stress strain curves of glass polypropylene composites with woven and biaxial weft knitted reinforcement

Rys. 4. Krzywa odkształcenie-naprężenie polipropylenu wzmocnionego tkaniną szklaną z wątkiem dwukierunkowym

MATERIAL MODELS

On the basis of the experimental results, phenomenological material models were developed that describe the strain rate dependent deformation and failure behaviour of the considered glass fibre reinforced polypropylene composites. The models consider the complex phenomena occurring on the atomic, microscopic and mesoscopic scale while they use a mesoscopic formulation.

To describe the strain rate dependent deformation behaviour, adapted rheological models of single composite component glass fibre and thermoplastic matrix are combined. Applying these models, it is possible to predict the strain rate dependent deformation behaviour for various fibre matrix combinations and different lay-ups. The advantage of this approach is that it is sufficient to determine the basic model parameter of the composite components, which reduced the effort of material characterisation.

To model the strain rate dependent failure behaviour, the Puck failure criteria were modified. These criteria that originally were developed for fibre reinforced composites with brittle matrix systems consider fibre and inter fibre failure separately. On the basis of the performed failure tests at different loading speeds, it was demonstrated that the relevant failure modes of the considered fibre reinforced thermoplastic composites were brittle, even if the separate thermoplastic matrix itself behaves in a ductile manner. Therefore application of the modified Puck criteria is reasonable. To model the influence of the loading speed on the strength in the fibre direction, strain rate dependent coefficients were introduced. These coefficients have to be determined experimentally in materials tests.

A comprehensive description of the mentioned deformation and failure models can be found in [2].

CONCLUSIONS

The comprehensive experimental investigation and the developed material models provide the basis for the generation of simulation models of complex loaded fibre and textile reinforced thermoplastic components under highly dynamic loading. These numerical models enable for the first time the efficient and reliable prediction of the complex deformation and failure behaviour of novel thermoplastic composite components in dependence of the strain rate, whereas the experimental effort to determine the material parameters can be reduced considerably.

The developed models were already used successfully for the first numerical crash and impact simulations on plane and cylindrical thermoplastic composite components [2, 8].

Acknowledgements

The authors gratefully acknowledge support within the collaborative research centre SFB 639 (partial project C4) at the Technische Universität Dresden funded by the Deutsche Forschungsgemeinschaft (DFG)

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