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Structural mechanic material damping in fabric reinforced composites: a review

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ABSTRACT

Purpose: A review regarding the acting mechanisms of structural dynamic material damping in fabric reinforced composites is presented.

Design/methodology/approach: Mechanical acting principles identified by different investigations are considered. Aspects of the determination and calculation of structural mechanical material properties of fabric reinforced composites are described. Approaches intending the description and classification of ondulations in fabrics reinforced single layers are demonstrated.

Findings: The mesomechanic geometry of fabrics is not considered sufficiently by relatively simple homogenization approaches. Yet, it significantly affects its structural dynamic material properties, especially the dynamic ones.

Research limitations/implications: In each case the different damping mechanisms act coupled and occur at the same time. Therefore a separation procedure is required in any case.

Practical implications: Against the background of the comparison and remarks of the presented papers a reasonable further procedure is recommended. Thereby, FE-calculations with a parametrical variation of the mesomechanic geometry in order to identify kinematic correlations due to geometric constraints are suggested.

Originality/value: The idea of the representation of the geometric conditions in terms of a degree of ondulation is described. Such a non-dimensional specific value representing the intensity of the ondulation would enable the comparability of the results of different kinds of investigations.

Keywords: Fibre reinforced plastics, Mesomechanic scale, Fabric reinforced layer, Ondulation, Review

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LITERATURE REVIEW

1. Introduction

Nowadays the use of fibre reinforced plastics become indispensable in many areas in industry. The feature of high stiffness and strength which simultaneously combine low mass allows new design approaches for weight loss, which leads to energy savings, for example in the automotive and aircraft industry.

Simplified theoretical approaches for fibre reinforced plastics often presume a layup of only unidirectionally reinforced single layers. As a first approach in applied engineering the structural mechanic properties can analytically be determined by the use of so-called micromechanical homogenization theories. These are usually based on the single components' properties, namely matrix and fibre. However, different kinds of fabrics are often applied as reinforcements in the layup of structural parts. In this case homogenization theories reach their limit. The reason therefore is that the mesomechanic geometry of fabric reinforced single layers cannot be considered sufficiently by relatively simple homogenization approaches. Yet, mesomechanic correlations are distinctly different as they significantly influence the mechanical properties of a structure.

2. Selected aspects

Selected papers regarding relevant aspects of material damping in fibre reinforced composites are presented. Amongst others, papers treating the influence of characteristic mesomechanic geometries in fabric reinforced single layers on the structural mechanical behaviour are considered. Contributions regarding the analytical and/or numerical consideration of the structural mechanical material damping in fibre reinforced plastics as well as the determination by experimental methods, e.g. for validation issues are relevant.

2.1. Different mechanical acting principles

Previous investigations and corresponding mechanical models regarding the structural dynamical damping behaviour of fibre reinforced plastics have been published amongst others by Kehl 1978 [26], Klug 1977 [27], Hanselka 1992 [18], Hoffmann 1992 [21] and Moser 1992 [35]. The theoretical approaches for the description of the damping behaviour are mostly based on the introduction of homogenization approaches as rules of mixtures, based on the properties of the single components, namely reinforcement fibres and polymeric matrix system. However, in several of the previously named works, the influence of the reinforcement fibres is already neglected because of their multiply higher stiffnesses and much lower visco-elastic properties, compared to the polymeric matrix system. Furthermore, the different approaches presume ideally micromechanical and mesomechanic geometries of the laminate, and at the same time neglect imperfections. These two strongly simplifying presumptions can be considered as the reason why experimentally determined damping properties of structures or specimens of fibre reinforced plastics mostly are slightly higher, than the theoretically calculated values. Figure 1 illustrates the model used in [26] for the analytical determination of the complex stiffnesses in transverse fibre direction. The glass fibres are presumed with a square cross-section in an evenly and repeating array. In order to obtain a solution, geometric compatibility has to be assumed. Yet, the matrix properties dominate due to its higher absolute values and due to additionally weighing the average.

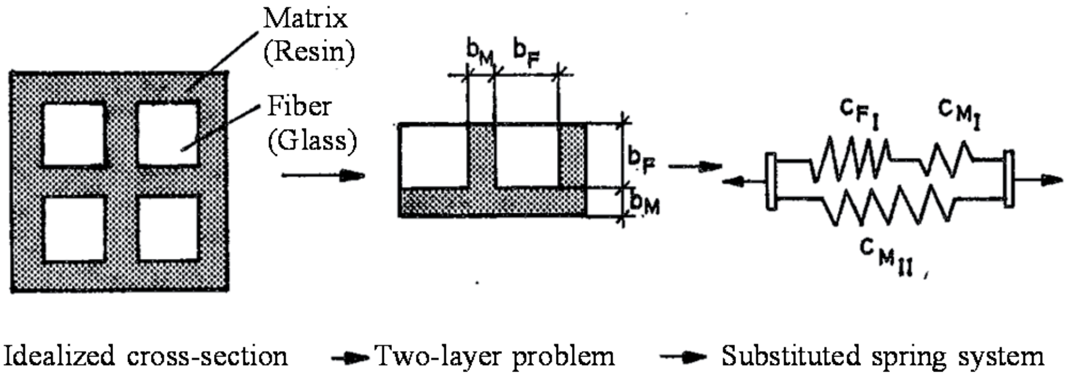


Fig. 1. Model used by Kehl 1978 [26] for analytical determination of the complex stiffnesses in transverse fibre direction

The review of Chandra, Singh and Gupta 1999 [11] gives a detailed classification and description of the different acting principles of structural dynamic material damping in fibre reinforced plastics. Thereby, five damping mechanisms are identified and described further. These are in detail:

1. Visco-elastic behavior of the matrix material and/or reinforcement fibres – the material damping of the matrix system is considered as the highest amount. The damping of the reinforcement fibres further contributes to the material damping of the composite material.
2. Damping due to the interphase – the fibre-matrix interphase is chemically different to the fibre and to the matrix. It consists of a mixture of sizing and matrix, and is called interphase. The sizing is applied on the reinforcement fibres as a protective layer and an adhesion-promoting agent. Depending on the applied amount on the fibre, the composite material partially consists of a no longer negligible volume content of interphase. Because its mechanical material properties essentially differ from the ones of the fibre and matrix, its influence on the damping behavior is not negligible, cf. Chandra, Singh and Gupta 2003 [10] and Kumar, Chandra and Singh 2007 [29].
3. Damping due to damages, – in regions of insufficient intralaminar or interlaminar adhesion (between fibre and matrix and delaminations between the single layers, respectively) damping effects due to the relative motion and resulting friction effects occur. Regions with cracks in the matrix or broken fibres additionally contribute to the material damping, cf. Pongratz et al. 2017 [45].
4. Visco-plastic damping and – high vibration amplitudes and corresponding high concentrations of strains cause high stress levels, that again cause an enhancement of the material damping. Additionally, these effects are partially non-linear. Thereby, visco-plastic damping is already in the linear-elastically presumed region of the material behavior no longer negligible.
5. Thermo-elastic damping – the damping mechanism is based on the alternating heat flow from the regions of compressive stress to them of tensile ones. This damping mechanism contributes to the material damping especially in the case of thermoplastic matrix systems.

It is emphasized, that the previously listed damping mechanisms are coupled and act at the same time. With regards to content, an essential part of the work especially considers damping due to damages, and the corresponding potential as an indicator for the material condition and for the structural integrity.

In Kumar, Chandra and Singh 2007 [29] the influence of the interphase as an adhesion-promoting agent between the reinforcement fibres and the polymeric matrix system on the damping in fibre reinforced plastics is considered. The carried out FE-calculation with the so-called three-phase-model, in which on a micromechanical scale the reinforcement fibre, the interphase and the matrix material are modeled, show the influence of the parametrically varied material properties of the interphase on the damping properties. Thereby a significant influence of the configuration of the interphase on the damping properties of the material is identified. Additionally, different micromechanical arrangements of the reinforcement fibres in the cross-section are investigated, that influence the damping behavior, too.

Chandra, Singh and Gupta 2003 [10] describe the underlying FE-analyses considering the influence of the interphase on the damping behavior by the strain energy method. Thereby, a two- and a three-dimensional micromechanical model of glass fibre reinforced epoxy is investigated. A case-by-case analysis for a so-called “hard” and “soft” interphase is carried out. Thereby, a hard interphase is assumed with the average of the elastic properties of fibre and matrix, and a soft interphase is considered with lower elastic properties than the pure matrix. At a constant fibre volume fraction of 40 % the interphase volume fraction is parametrically varied in the selected steps of 2%, 4%, 8% and 10%. Fig. 2 exemplarily illustrates the two- and the three-dimensional FE-model of the three-phase model under transverse loading conditions. Transverse shear, longitudinal stress and longitudinal shear loading conditions are considered further. The results give an insight on the interplay and the relative contributions of the three single components to parametrically varied loss factors and volume fractions. Fig. 3 shows the variation of the loss factors η_{11}, η_{22}, η_{12} and η_{23} over the parametrically varied interphase volume fraction V_i. They are determined by the strain energy method for the three-dimensional FE-calculations. Thereby, the interphase has been considered with so-called soft and hard elastic properties and a presumed loss factor of η_i=0.0084 as the average of the values for the fibre and matrix.

Klug 1977 [27] carries out analytical, numerical and experimental investigations regarding the damping behaviour of glass fibre reinforced plastics. Thereby, the parameters fibre, matrix, orientation of the fibres, kind of layup and fibre volume content are considered in detail. The following simplifying presumptions have been made:

- linear visco-elastic behaviour of the matrix material and of the reinforcement fibres,
- no frequency dependency of the damping,
- no stress dependency of the damping due to the presumption of viscous damping behaviour,

- experimentally determined damping values at low stress levels can be considered as real material properties and do not require any correction,
- composite material with ideal adhesion between fibre and matrix with no damages and imperfections.

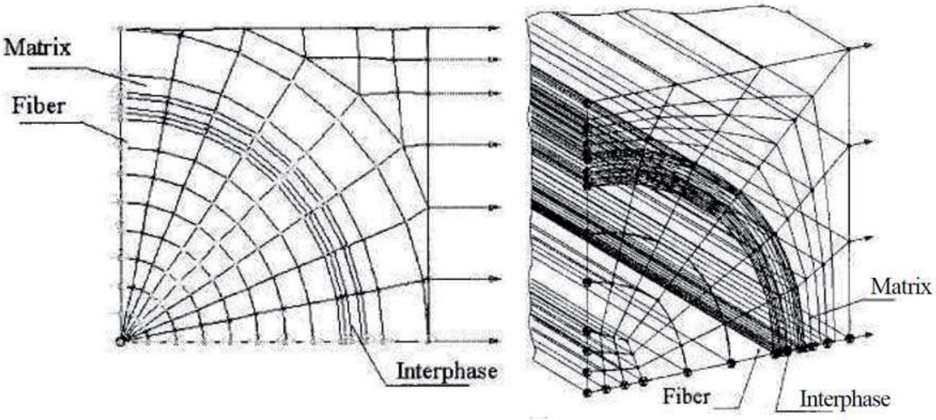


Fig. 2. FE-model for the consideration of the three single components fibre, interphase and matrix [10]: 2D-model (left) and 3D-model (right) under transverse loading

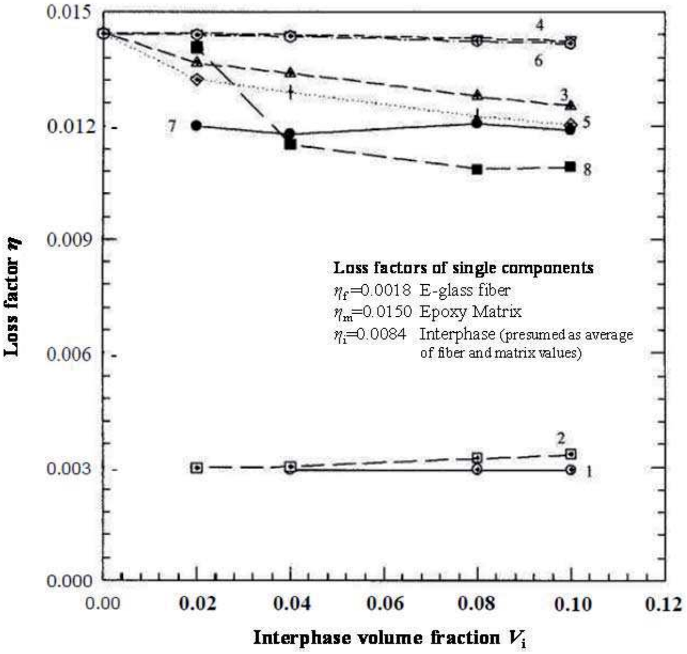


Fig. 3. Effect of the interphase volume fraction V_i on the loss factors η for soft and hard interphase for the 3-D FE-model [10]: 1 η_{11} soft, 2 η_{11} hard, 3 η_{22} soft, 4 η_{22} hard, 5 η_{12} soft, 6 η_{12} hard, 7 η_{23} soft, 8 η_{23} hard

Thereby, at low stress levels and in mint conditions (i.e. unstressed in any aspect before the experimental investigation) the specimens yield very good correlation between theoretically calculated material damping and experimentally determined ones. At low amplitudes and thereby low stress levels hysteresis damping and viscous damping correspond. In detail flat beam-like specimens and tubes as circular cylindrical shells are experimentally investigated. In both cases reproducibly introduced micro-cracks enhance the material damping, determined experimentally in the flexural vibration test. The increase of the material damping correlates with the decrease of the stiffness, whereat the increase of the material damping is always higher than the decrease of the stiffness. Because mainly the harmonic vibrations beams in the flexural vibration test of the flat beam-like specimens exhibit linear damping properties in large ranges, it is suitable for the experimental determination of the material damping and for the validation of results of analytical and/or numerical investigations. Figure 4 illustrates the correlation between applied pre-strain in a quasi-static bending test and resulting enhancement of material damping for circular cylindrical tubes. In detail two kind of layups of glass fibre reinforced plastic have been investigated. The measurements have been carried out in direction of the applied load and perpendicular to it. The results of the pre-loaded structure are related to the ones in the intact undamaged conditions. It is stated, that a beginning failure can be predicted with a sufficiently high liability. The sensitivity of damping and the insensitivity of stiffness in terms of eigenfrequency is underlined.

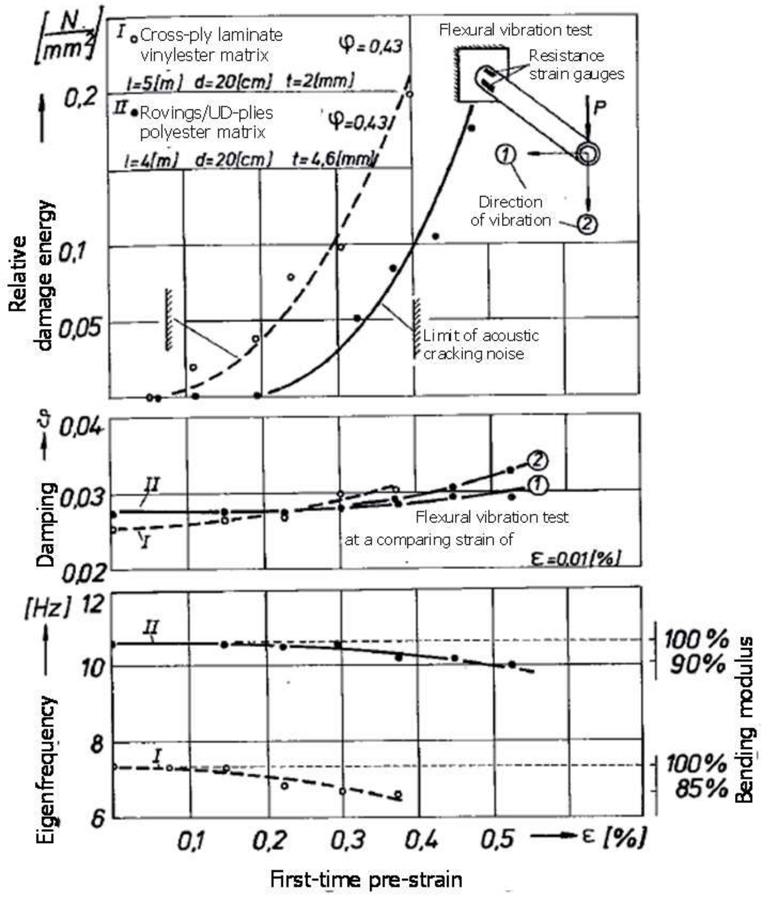


Fig. 4. Enhancement of material damping caused by micro-cracks in winded circular cylindrical tubes due to selected reproducible pre-loading the structure by bending [27]

Tauchert 1974 [58] shows the possibility of the extrapolation of the material damping of fibre reinforced plastics over large frequency ranges. In order to investigate ranges of high frequencies, unidirectionally reinforced specimens are excited by ultrasonic sound parallel and transversal to the orientation of the fibres. Results of previously carried out experimental investigations of flat beam-like specimens with unidirectionally reinforced glass fibre reinforced plastics, that have been investigated under excitation by vibrations of an electro-mechanical shaker for low and mid frequency ranges, are used as a data base. It is shown, that an extrapolation of the material damping over very large frequency ranges is possible.

Against the background of the requirements in the automotive and aerospace industry Sun, Rao and Sankar 1992 [55] investigate the optimization of damping properties of fibre reinforced plastics. Therefore, FE-calculations and experimental investigations are carried out with the aim to determine the passive damping in fibre reinforced plastics. The FE-calculations consider both an unstressed and a pre-stressed material. Yet, only the unstressed case can be validated in the flexural vibrating test.

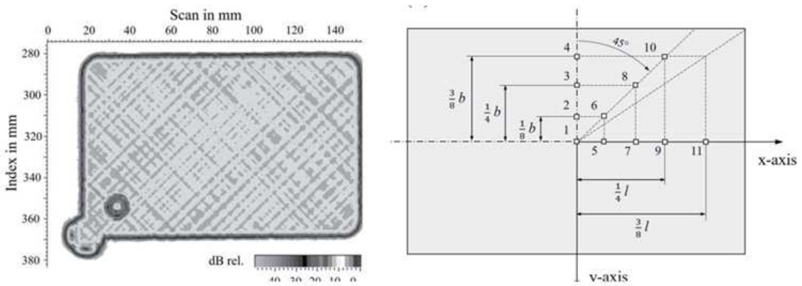
In Tsai and Chi 2008 [59] the influence of the micromechanical array of the reinforcement fibres on the damping behaviour of unidirectionally carbon fibre reinforced plastics is investigated numerically. Three different fibre arrays, i.e. the square edge or quadratic packing, the square diagonal packing and the hexagonal packing are considered as ideal arrays by investigating representative volume elements (RVEs). Thereby, the quadratic packing yields higher damping properties than the other two packing arrays. The determined material properties of the RVE are extrapolated on one- and two-dimensional structures (beams and plates). These are modelled by plane specimens that are relatively short and thick, and thereby not completely relevant for real applications. It is concluded, that the micromechanical fibre array significantly affects the damping behaviour.

In Hwang and Gibson 1992 [23] for a further analysis and description of different damping mechanisms acting in fibre reinforced plastics FE-calculations in the micromechanical and in the macromechanical scale are carried out. They are evaluated by the strain-energy-method. In the macromechanical scale, amongst others, coupling effects are considered, that caused by the kind of layup act as additionally energy dissipating mechanisms. In detail bend-twist coupling in symmetric layups and bending-extension coupling in anti-symmetric layups are identified as the effects of enhanced damping.

The review of Finegan and Gibson 1999 [14] describes the state of the art regarding enhancement and optimization of damping properties in fibre reinforced plastics. The motivation therefore is the requirement of improved damping properties regarding the minimization of noise emissions, the enhancement of dynamic stability, the enhancement of fatigue resistance and the resistance against transversal impact damages. In the macro-mechanical scale couplings in the laminate are treated as additional energy dissipating mechanisms, analogue to [23]. Additionally the acting of a structural dynamic damping mechanism in fabric reinforced single layers of fibre reinforced plastics is mentioned explicitly, but not treated further. Instead of that the influence of the fibre volume content on the damping behaviour is investigated more in detail. Thereby, specimens with layups of fabric reinforced single layers are considered.

The review of Gibson 2000 [15] the state of the art and results of investigations regarding the possibility of characterization of fibre reinforced plastics by structural dynamical material properties are presented. Amongst others the possibility or the potential of mechanically characterizing the material condition or the structural integrity is emphasized. Thereby, different advantageous aspects result. The mechanical characterization of fibre reinforced plastics by structural dynamic investigation, especially the determination of elastic and visco-elastic material properties, is time and cost saving as well as precise. Yet, different clamping mechanisms as the boundary conditions are indicated as the difficulty regarding the validation of analytical models by experimental results. In analytical models often all side simply supported edge conditions for structures are presumed, in order to achieve analytically closed results. In contrast, the experimental determination of the material properties, amongst others due to practicability and reproducibility, an all side clamped or fixed edge condition is required. Consequently, the corresponding analytical solution is then possible only by analytical approximation methods, such as exemplarily according to Rayleigh, Rayleigh-Ritz or Galerkin.

Pongratz et al. 2017 [45] investigate the influence of low-velocity impact damage on the structural dynamic behaviour of composite plates. As impact damages occur inside the structure, the investigations aim at the damping effects due to internal damages, as indicated in [11]. The vibrational behaviour of the composite structure is focused as an alternative to time consuming ultrasonic testing. The vibrational approach takes into account response frequencies and especially the modal damping. The plate-shaped specimens are experimentally investigated in an intact state as well as in an impact damaged state by structural dynamic measurements. For a contactless measurement a laser scanning vibrometer is used. The oscillation of the specimens is realized by acoustic excitation. The boundary condition is free, as it is realized by a thread suspension. The single response frequencies already prove a damage indication. However, this is insufficient, because the indicated frequency shift is subtle and in addition strongly dependent on its present bearing. A normalization of the different plate-shaped specimens based on its excitation and frequency sweep speed is rather difficult. Thus, statements concerning the material integrity are only completely reliable, if vibrational characteristics prior to the impact damage are available, too. The results show, that the damping and loss modulus in particular, increase significantly with an impact damage. The impact damage appears to be in direct correlation to the material damping. Amongst others, material integrity statements based on the damping ratio of composite plates are considered promising. Amongst others a series of six specimens produced with prepregs in autoclave processing is considered in detail. The cross-ply laminate $[[0/90]_2]_S$ with t=1.7 mm consists of eight unidirectionally carbon fibre reinforced single layers with epoxy matrix. The plates have geometric dimensions of 150 mm x 100 mm. The energy of the low velocity impact damage is 5.5 J, and was applied in the centre. The measurement points are equally distributed on the first quadrant as a representative area of the plate. Exemplarily the eighth eigenmode has been considered further. Excluding two singularities the average increase of damping due to impact damage is approx. 5.3% at the measurement points, as illustrated in Figure 5. In contrast the eigenfrequencies only shifted in a very small range. In percentage terms the decrease was only about 0.07%, and are additionally assumed to the influences of the bearing rather than of the impact damage.



Ultrasonic C-Scan of intact specimen

Positions of measurement points

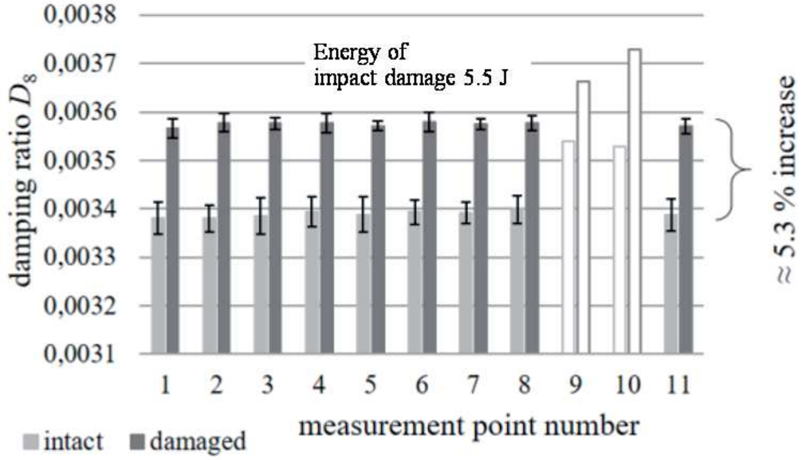


Fig. 5. Enhanced material damping of 5.3% due to an impact damage of 5.5 J on a cross-ply laminate of carbon fibre reinforced plastic at equally distributed points [45]

In Romano 2016 [46] and in the corresponding underlying works of Ottawa et al. 2012 [43], Valentino et al. 2013 [61], Romano et al. 2014 [48], [49], Valentino et al. 2014 [61] and Romano, Ehrlich and Gebbeken 2017 [47] a mesomechanic kinematic in fabric reinforced single layers due to geometric constraints only is introduced. Therefore, an analytical and a numerical identification of a mesomechanic kinematic in fabric-reinforced single-layers as well as its validation by the structural dynamics of flat beam-like specimens of carbon-fibre reinforced plastic (CFRP) is carried out. Under the presumption, that the repeated acting of the kinematic dissipates energy, it contributes under cyclic viscoelastic deformation to the pure viscoelastic material damping of fabric-reinforced single-layers. The analytical and numerical investigations consider the plain, two-dimensional correlation of one complete ondulation and a representative sequence, respectively, in the through-thickness direction. In order to identify the parameters, the geometric dimensions are varied in defined steps. Therefore the degree of ondulation in fabric-reinforced single layers $\tilde{O}=A/L$ is introduced as a dimensionless ratio. Fig. 6 illustrates the analytical results of the identified mesomechanic kinematic and the degree of ondulation over the geometric parameters. In order to validate the contribution of the analytically and numerically identified mesomechanic kinematic in fabric-reinforced single-layers to the material damping, the free decay of transversal vibrations of single-sided clamped specimens is considered in the experimental structural dynamic investigations. In detail flat beam-like specimens of carbon-fibre reinforced epoxy with layups of 0°-unidirectionally reinforced and fabric-reinforced single-layers are investigated. The results of the experimental structural dynamic investigations are shown in Fig. 7. They allow the validation of the analytical model and the numerical calculations. The contribution of the identified mesomechanic kinematic is finally quantified depending on the introduced degree of ondulation $\tilde{O}$.

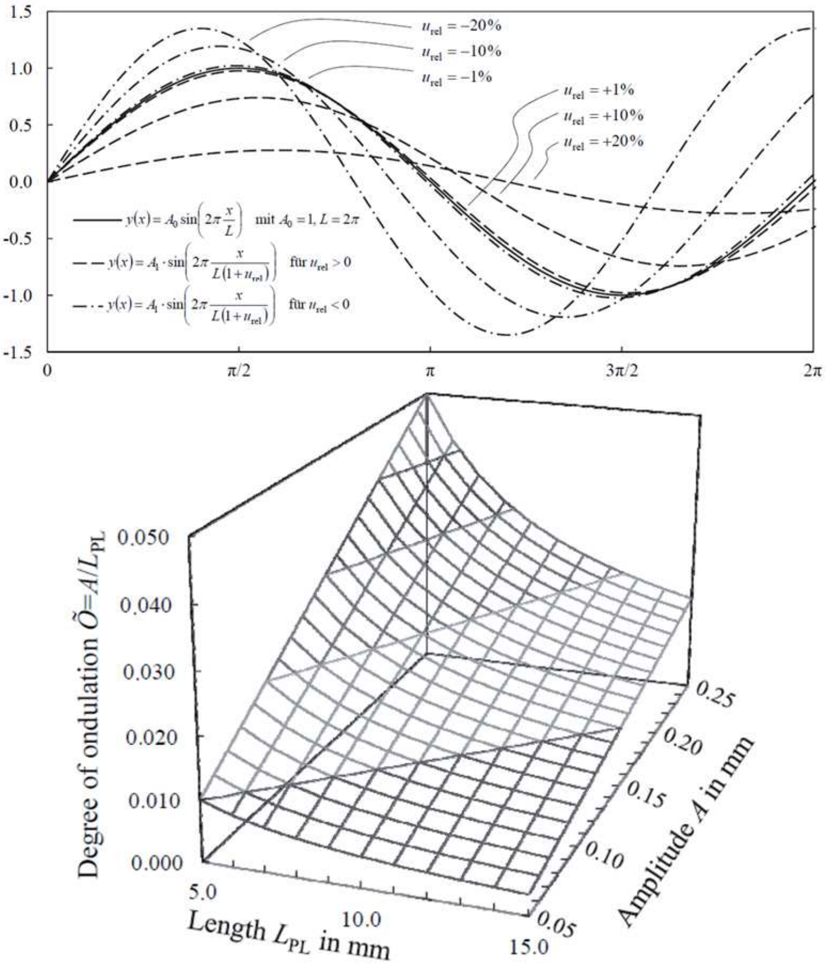


Fig. 6. Analytical results of the mesomechanic kinematic (top) and introduced degree of ondulation $\tilde{O}=A/L$ (bottom) [47]

2.2. Determination of structural dynamic material properties

The two publications of Schultz and Tsai 1968 [52] and 1969 [53] present the experimental determination of the dynamic stiffnesses and damping properties of fibre reinforced plastics under excitation over a relatively large frequency range. Therefore flat beam-like specimens of unidirectional glass fibre reinforced epoxy have been used. Different orientations of the cut out specimens on the test panels provide eight different kinds of layups of the specimens. They are clamped in the middle of its length, so that the specimen can mechanically be considered as a symmetric cantilever beam.

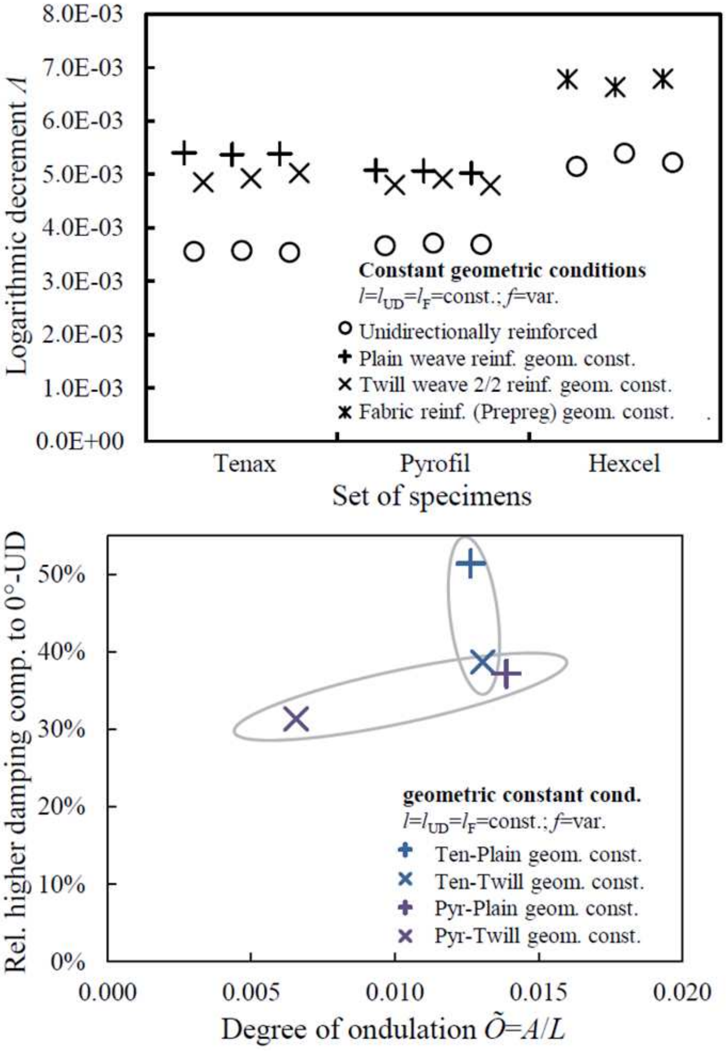


Fig. 7. Material damping of UD- and fabric reinforced specimens: absolute values (top) and relative proportions (bottom) [46]

The clamping is excited by an electro-dynamic actuator from the 1st to the 27th natural frequency with constant amplitude. At each excited natural frequency omission of the excitation a free-decay process can be observed. The statically determined stiffnesses are smaller of 20% to 27% regarding the dynamically determined stiffnesses (in terms of the storage and loss modulus). The evaluation of the results shows a relatively low dependency of the storage modulus on the frequency, where it has been determined. In contrast the loss modulus distinctly depends on the corresponding frequency. With increasing amplitudes in general the evaluated material damping increases. Additionally, a shorter evaluated period (10 cycles) always yields higher material damping than a longer one (50 cycles). Thereby, experimentally determined loss moduli are always equal or slightly higher, but never smaller, than the analytically determined ones. As the reason therefore a complex stress state, especially between the single layers of the laminate (interlaminar), is supposed. A sensitivity analysis shows that regarding the increasing amplitude of the excitation the frequencies are insensitive, but the damping values are sensitive. Regarding the sensitivity of the experimentally determined results, measurements have been carried out in evacuated atmosphere, too, but yield no significant influence on the values measured under ambient/laboratory conditions.

The work of Kadioglu 2009 [25] describes the experimental determination of the structural dynamic material properties, namely stiffness and material damping of fibre reinforced plastics. Thereby, initially the experimental methods of determination of the static and dynamic structural mechanic material properties are confronted. Whereat the static methods mostly are destructive, and exhibit relatively high variances in the range of percent, the dynamic methods are mostly non-destructive, time- and cost saving, and exhibit smaller variances of approx. one decade. Two-sided simply supported specimens are investigated, whereat the position of the support is at the nodes of the first natural form. The excitation and the measurement are done contactless. Thereby, carbon and glass fibre reinforced plastics, produced of prepregs by autoclave-processing, are investigated. The experimental results are validated with measured values of specimens of steel and aluminium. The amplitude of the excitation is constant and held as small as possible, in order to avoid possible (geometric) non-linearities. The contactless excitation and the measurement at free-free boundary conditions are considered advantageous compared to other methods and boundary conditions.

Motavalli and Flüeler 1998 [36] consider selected American standards, and where possible European and parallel German standards, too, that contain essential aspects regarding the experimental mechanical characterization of fibre reinforced plastics. Its underlying methods are classified into two categories. The first one contains investigations for a basic characterization of a first series of specimens of a new layup. The second one contains recommended methods regarding material quality issues. Each method is referred to the respective standards and briefly described. A carbon fibre reinforced laminate with a layup of unidirectionally reinforced single layers serves as an exemplary layup of specimens. As an adequate experimental method regarding the determination of the dynamic material properties the flexural vibration test of a cantilever beam according to DIN 53440 [37] is indicated.

The work of Mistou and Karma 2000 [34] compares the destructive tensile test and the non-destructive measurements of impedance of induced ultrasonic sound as experimental methods for the determination of three-dimensional independent structural mechanic material properties of stiffness and Poisson's ratio of fibre reinforced plastics. Different textile semi-finished products of glass fibres in unsaturated polyester resin as a matrix system are considered. In detail it is about a 0°-unidirectionally reinforced laminate of rovings, a 0°-unidirectionally reinforced laminate of UD-strands and two plain-weave fabrics with different areal weight. The variance of the fibre volume content over the different kinds of layups is relatively high. However, in order to make the results of the experimental investigations comparable, the evaluated material properties are standardized by rules of mixtures to a fibre volume content of 45 %. The variances of the results of the two experimental methods lie in a range of < 10%. The variances are explained amongst others by the standardization of the experimentally determined material properties. A tendency, which methods provides higher or lower values, cannot be identified. Due to the relatively low expenditure of time and cost the non-destructive method for the determination of (quasi-)static material properties is favoured.

Vantomme 1995 [62] presents parametrically analytical calculations and experimental investigation for the determination of the material damping in fibre reinforced plastics. The analytical calculations consider the damping properties of the single components, namely reinforcement fibres, polymeric matrix system and interphase. Based on the strain-energy of a representative volume element (RVE) analytically closed solutions are indicated. The selected approach weights the contribution of the single component to the material damping with the respective part of the elastic strain-energy. This value depends on the elastic properties of the single components. In order to investigate the influence of the interphase, additionally a three-parameter-model is formulated. The model shows a significant increase of energy-dissipation-capacity of a unidirectionally reinforced single layer at a low quality of the interphase, i.e. low stiffness of the interphase and thereby a bad fibre-matrix-adhesion. For a validation of the analytical results unidirectionally glass fibre reinforced specimens with epoxy matrix are investigated experimentally. Depending on two different unsupported lengths two different qualities of the interphase result. Beam-like and plate-like specimens are excited by the contactless method of acoustic sound pressure, and after omission of the excitation the free decay of the vibrations is measured by the contactless method of a laser-doppler-vibrometer. The influence of the damping enhancing bad quality of the interphase can be proved. In the outlook for the description of the material damping of damaged materials an additional contribution due to Coulomb friction is named explicitly, that is not negligible in this case.

The papers of Schmidt 2003 [51] as well as of Schmidt and Gaul 2007 [50] contribute to the modelling and experimental determination of linear-viscoelastic material behaviour. In case of the modelling of the material damping, besides integer time-derivatives, especially their extension to fractional time-derivatives are focused. The extension to fractional models of linear visco-elasticity is introduced by the definition of fractional derivatives according to Riemann-Liouville. The used specimens consist of the unreinforced thermoplastic material Polyoxymethylen. Besides investigations in a shear-rheometer, the free-decay of transversal vibrations of one-sided clamped specimens is measured contactless by a laser-doppler-vibrometer. For the excitation of the specimens at different relevant natural frequencies, the unsupported lengths and the thickness of the specimens are varied in selected steps. In order to mechanically describe the transversal vibrations of the specimens the shear-stiff beam-theory according to Euler-Bernoulli is applied. The evaluations show, that the modelling of linear-viscoelastic material behaviour with fractional time-derivatives provides correct results over larger time and frequency domains, compared to the modelling with classic spring-dashpot-models. The results are used for the implementation in FE-formulations of visco-elastic materials with fractional time-derivatives.

2.3. Ondulations in fabric reinforced single layers

Several publications treat the structural mechanic behaviour of ondulations in fabric reinforced single layer. Fig. 8 exemplarily illustrates selected schematic cross-sections of ondulations used for the structural mechanic description of fibre reinforced plastics with fabric reinforcement. Thereby, mainly 0°/90° plain-weave fabrics are considered. Others even include rarer textile constructions, such as twill-weave and satin.

Byun 2000 [9] presents an analytical model of a so-called unit-cell in a mesomechanic scale in order to calculate the geometric character and the three-dimensional structural mechanical material properties of layups of two-dimensional breaded textile semi-finished products. Based on an ideally presumed mesomechanic geometry, the continuously differentiable varying orientations of the ondulating rovings is analytically indicated and validated by photomicrographs. Analogue under the presumption of a constant fibre volume content in the ideally impregnated rovings the calculation of the global fibre volume content of the layup and the laminate, respectively, is indicated. The elastic model uses the coordinate transformation and the weighted average of the stiffnesses and compliances of the single components (fibre and matrix), respectively, based on the fibre volume content. For the validation of the analytical calculations seven different kinds of fabric constructions have been produced and experimentally investigated by one-dimensional tensile tests. The results of the analytical model are additionally compared to results, that are based on the classical lamination theory (CLT). The results of both analytical methods correlate with the experimental results. Yet, the introduced analytical model, based on the mesomechanic unit-cell, provides more precise results at low angular deviations or at distinctly different dimensions of the rovings in the textile semi-finished product. Therefore, a parameter variation has been carried out for the introduced analytical model. The results are indicated at selected stiffnesses and Poisson's ratios.

Huang 2000 [22] treats the structural dynamical material properties of laminates with layups fabric reinforced or breaded single layers. The analytical description of a representative sequence of a plain-weave fabric in the mesomechanic scale leads to the introduced bridging model. It describes the structural mechanical behaviour of laminates of fabric reinforced or breaded single layers. For a detailed analytical description a balanced plain-weave fabric as a two-dimensional textile semi-finished product is presumed. The introduced model allows the description of linear-elastic and plastic correlations as well as the consideration of strength aspects of fabric reinforced layups under arbitrary loading conditions. Thereby, the stress states of the single components directly depend on the global loading of the composite material, so that the global behaviour of the composite material can directly lead back to the structural mechanic behaviour of the single components. The simplified geometry presumes an elliptic cross-section as well as a sine-shaped ondulation of the rovings. The presumed geometry causes three structural mechanic different regions in the representative sequence. These are namely, the perpendicularly crossing and ondulating warp and fill yarns, presumed as unidirectionally reinforced, and regions of pure matrix without any fibre reinforcement. For verification issues several geometric parameters of the model have been analysed. The results of the stiffnesses and strengths of the analytical model agree very well with the experimental results. Additionally, the influence of voids on the stiffness and strength has been investigated parametrically.

Le Page et al. 2004 [30] present two-dimensional FE-calculations under the presumption of a plane strain state, in order to investigate different local geometries of fabric reinforced single layers regarding the damage propagation depending on the number of single layers. Thereby, the global stiffness is relatively insensitive to a variation of such kind of local geometries. In contrast, the position of a crack strongly affects the rate of released strain energy in correlation with the form of the crack. Parametric investigations of layups of plain-weave fabric reinforced single layers in the so called in-phase and out-of-phase arrangement are carried out. The mesomechanic geometry, once again, presumes elliptic cross-sections and a sine-shaped ondulation of the rovings, so that the three structural mechanic different regions in the representative element follow (unidirectionally reinforced warp and fill yarn and pure matrix without any fibre reinforcement). Against this background the parametric investigations are carried out.

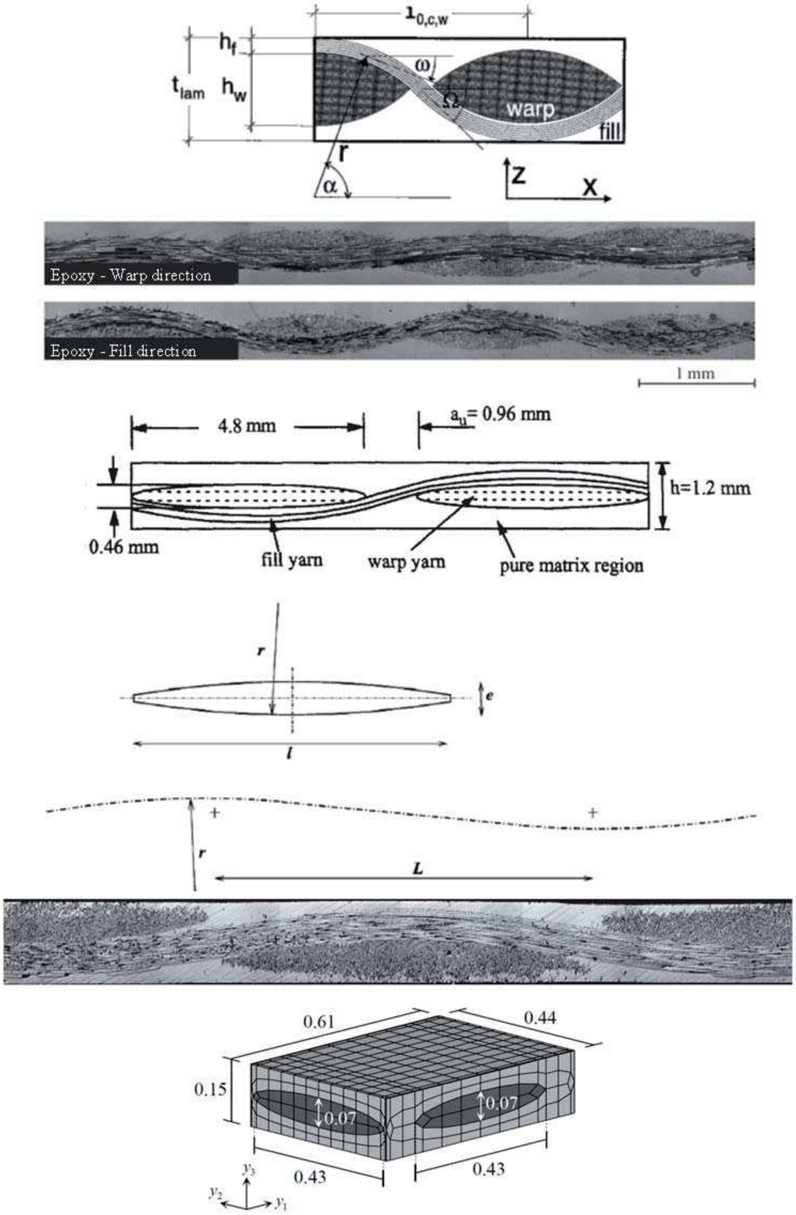


Fig. 8. Exemplarily selected cross-sections from publications treating ondulations in fibre reinforced plastics with plain-weave fabrics (from top to bottom): Stellbrink 1996 [54], Ballhause 2007 [3], Guan and Gibson 2001 [17], Badel, Vidal-Sallé and Boisse 2007 [2], Nakanishi et al. 2007 [42] and Matsuda et al. 2007 [31]

Szablewski 2009 [56] treats representative sequences of plain-weave fabric reinforced single layers under the simplifying geometric presumption of a sine-shaped ondulation of the rovings in the mesomechanic scale. The model provides the determination of relevant geometric parameters in the mesomechanic scale, so that the mesomechanic geometry of the textile semi-finished product is definitely defined. The mesomechanic geometry presumes an elliptic cross-section and a (quasi-)sine-shaped ondulation of the rovings. Yet, in this case, too, the mesomechanic geometry presumes elliptic cross-sections and a sine-shaped ondulation of the rovings, so that the three structural mechanic different regions in the representative element follow (unidirectionally reinforced warp and fill yarn and pure matrix without any fibre reinforcement). During further progress the strength analysis is focused. Finally, the adaption of the presumed mesomechanic geometry to other kinds of fabric construction is indicated.

Tabiei and Yi 2002 [57] compare methods for the determination of structural mechanic material properties of laminates of plain-weave fabric reinforced single layers. In detail it is about the method of representative volume elements (RVEs), the four-cell-method and the method of three-dimensional FE-calculations. As a further method a simplified version of the method of unit-cells of fabric reinforced layups is introduced. They differ basically in the simplifying presumptions of the mesomechanic geometry of a plain-weave fabric reinforced single layer. Whereas the method of representative elements presumes a continuously differentiable variation of the predominant direction an elliptic cross-section of the unidirectionally reinforced rovings, the four-cell-model presumes an area by area linear, and thus discrete, form of the predominant direction and a rectangular cross-section of the unidirectionally reinforced rovings. Additionally, the numerical efficiency and thereby the applicability and practicability of the single methods is considered. Results of numerical calculations of the structural mechanical properties of the presented methods are compared to each other. Thereby, the introduced method of unit-cells agrees very well to the other applied methods.

Wielage et al. 2005 [64] emphasize the relevance of a detailed structural mechanic description of laminates of fabric reinforced single layers, whereas for the calculation of laminates of unidirectionally reinforced single layers several analytical and numerical methods exist. The fabric reinforced single layers are presumed based on unidirectionally reinforced ondulated rovings. For a mechanical description the method of representative volume elements is used. Thereby a complete ondulation is modelled in the mesomechanic scale. The three investigated kinds of fabric constructions are namely a plain-weave fabric, a twill 2/2 fabric and a satin 1/4 fabric. The mesomechanic geometry presumes an elliptic cross-section as well as a sine-shaped, and thereby continuously differentiable, ondulation, so that in this case, too, the three structural mechanic different regions in the representative element follow (unidirectionally reinforced warp and fill yarn and pure matrix without any fibre reinforcement). Thereby, the independent structural mechanic material properties of the locally transversal isotropic impregnated roving are calculated according to rules of mixtures, based on the single components fibre and matrix. During further progress the structural mechanic stiffnesses (longitudinal, transversal and shear stiffness) and the thermal expansion coefficient for the single kinds of fabric constructions are calculated by FE-calculations and validated experimentally. Additionally, in case of the satin 1/4 fabric the influence of voids in the region of pure matrix without reinforcement is considered.

Mital, Murthy and Chamis 1996 [33] investigate the mesomechanic correlations in plain-weave fabric reinforced single layers with representative volume elements. The results are described analytically and verified numerically. The form of the ondulated unidirectionally reinforced rovings is modelled by sine-shaped sequences, that connect the linear regions of the ondulated rovings. In order to simplify and reduce the computation time, symmetry properties of the representative sequences are used. Thereby, based on analytical approaches the hygrothermal and the structural mechanic behaviour of the representative volume element are described. The results provide the complete thermal, hygroscopic and structural mechanical material properties of the plain-weave fabric reinforced single layer, and thereby the input values required for FE-calculations for a numerical dimensioning of structures. This finally provides the mechanical stress analysis in the laminate as well as the micromechanic stress analysis of the single components. In detail the analytical calculations are used, amongst others, for the calculation of carbon fibre reinforced epoxy with plain-weave fabric reinforcement, where the ondulation of the rovings is considered by the mesomechanic geometry as well as the kind of layup. Thereby, the results of the analytical calculations agree well both with the three-dimensional calculations and with the experimentally determined material properties. Yet, compared to the three-dimensional FE-calculations, the presented method is recommendable especially due to its numerical efficiency.

Naik and Shembekar 1992 [41] present two-dimensional models for the linear-elastic analysis of a plain-weave fabric reinforced single layer. The models describe the mesomechanic geometry by the consideration of a continuously differentiable ondulation of the rovings (both in warp and fill direction), a possible distance between the adjacent rovings, the actual shape of the cross-section as well as a possible unbalance of the plain-weave fabric. Investigations regarding the effects of the ondulation in fabric reinforced single layers and the thickness of the single layer on the plane structural mechanic material properties is presented. Thereby, a substantial discrepancy between the one-dimensional analytical and numerical models and experimental results follows. Due to the sufficient consideration of effects of the ondulation in two-dimensional analytical and numerical models, these models correlate very well with experimental results.

Ballhause 2007 [3] describes the structural mechanic behaviour of dry fabrics in the mesomechanic scale under uni- and bi-axial loading numerically and experimentally. A failure model is formulated, that is lead back to the increase of the contact forces and the simultaneously resulting reduction of the intensity of ondulation at the crossings of warp and fill yarns under increasing load. In detail a smaller degree of deformation causes a smoothing of flattening of the ondulated roving, and thereby a reduction of the thickness. A further positive deformation in one or two dimensions the smoothing or flattening of the loaded rovings even causes a rise of the perpendicularly crossing rovings. This mechanism results in an increase of the thickness of the fabric instead of a reduction of it, that is actually expected due to a coupling analogue to transversal deformation due to Poisson effects. Fig. 9 illustrates the structural mechanic behavior of an uniaxially loaded dry plain-weave fabric and the resulting deformations and stresses.

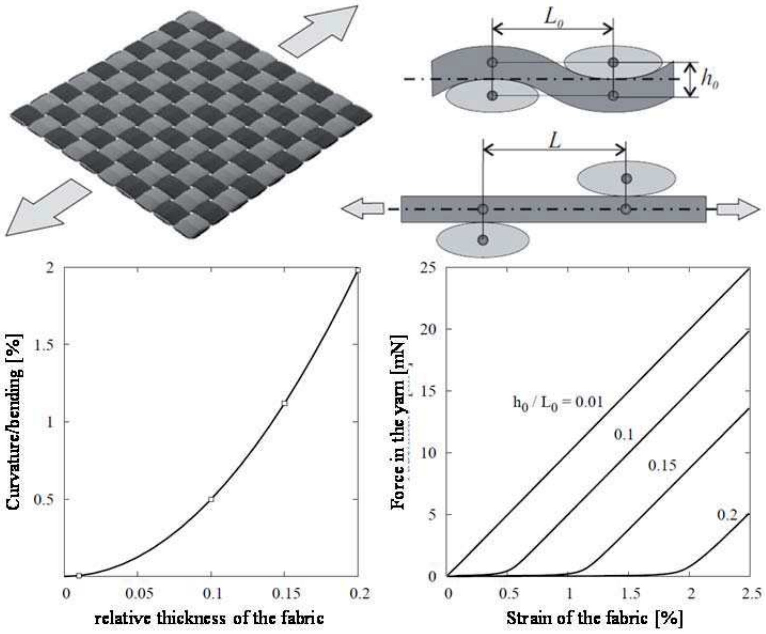
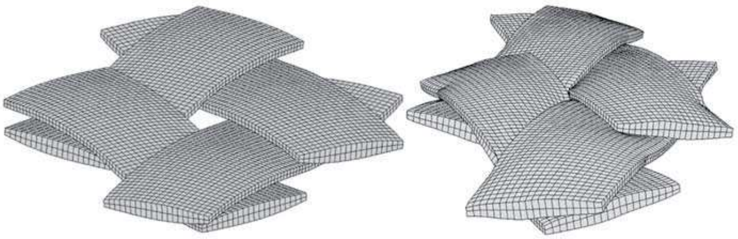


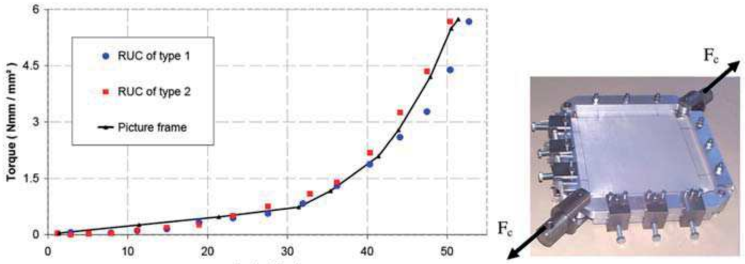
Fig. 9. Structural mechanic behaviour of an uniaxially loaded dry plain-weave fabric [3]: flattening of the initially ondulated yarn, curvature over relative thickness of the fabric and corresponding load-displacement curve

Badel, Vidal-Sallé and Boisse 2007 [2] investigate the mesomechanic material behaviour of dry fabrics under shear loading analytically, numerically and experimentally. In detail a dry plain-weave fabric is clamped in a so-called shear-frame-mechanism (also: picture-frame-mechanism or four-joint-frame) where shear loading is introduced by tensile loading at two opposite joints. At increasing loading, and thereby increasing shear-strain-rates, non-linearities regarding the resulting angle of the frame and the resulting orientation of the rovings in the fabric result. At sufficiently large shear-deformation the outer edges of the originally perpendicular warp and fill yarns get in contact. Further increase of the shear-deformation causes an increase of the thickness and finally a stability failure of the originally plane fabric, similar to buckling. Figure 10 illustrates the deformed FE-model at selected shear angles, the validation of the FE-calculations and the experimental picture frame setup.



FE-model at shear angle 28°

FE-model at shear angle 54°



Experimental and numerical shear curves

Experimental picture frame setup

Fig. 10. Deformed FE-model at selected shear angles, validation of the FE-calculations and experimental picture frame setup [2]

Hivet and Boisse 2008 [20] investigate the meso-mechanic material behaviour of dry fabrics under bi-axial loading analytically, numerically and experimentally. Thereby, a distinct non-linearity, especially at low loading levels, results. This yields, analogue to the effects reported in [3], initially a reduction of the thickness, but at further positive deformation an increase of the thickness of the dry fabric layer.

Hivet and Duong 2010 [19] investigate the meso-mechanic material behaviour of dry fabrics both under shear loading, analogue to [2] and [3], and under bi-axial tensile loading, analogue to [20], analytically, numerically and experimentally. In detail two dry plain-weave fabrics are investigated. The shear loading is introduced by a picture-frame-mechanism and the bi-axial tensile loading is introduced by a bi-axial tensile testing machine. In both cases an increasing loading and thereby increasing strain-rates yield the afore described non-linearities.

El Mahi et al. 2008 [13] give an analytical description of damping mechanisms in fabric reinforced single layers and carry out FE-calculations, that are validated experimentally, too. The numerical calculations are based on the consideration of the strain-energy under the presumption of plane stress and are limited to uni-directionally and orthotropic reinforced laminates due to the simplifying presumptions. In detail a 0°-uni-directionally reinforced laminate of UD-strands, a 0°-uni-directionally reinforced fabric (strongly unbalanced with 0° as predominant direction), a plain-weave fabric and a twill-weave fabric (both in warp direction) of glass fibres are investigated. The validation of the investigated damping mechanisms is carried out by flat beam-like specimens. These are cut out of test panels of glass fibre reinforced epoxy and subsequently prepared. They are one-sided clamped, excited by a mechanical impulse, and measured contactless by a laser-doppler-vibrometer. The variation of the investigated natural frequencies is done by a selected variation of the unsupported lengths at different geometric dimensions of the cross-sections. The sensitivity of the results to different experimental parameters as well as the reproducibility of the experimental procedure has been proved. Thereby, even the influence of the aerodynamic damping due to air-friction and viscous air-damping, respectively, as well as inertia effects have been considered. Yet, it appears, that the influence is significant only at large amplitudes of the vibrations, and is negligible at small ones. At identical predominant directions (0°-uni-directionally reinforced and reinforced in warp direction) the material damping of the specimens differs significantly for each kind of textile semi-finished product. In each case the results are illustrated for the first three natural frequencies of approx. 50 Hz, 300 Hz and 600 Hz. The 0°-unidirectionally reinforced laminate of UD-strands and the 0°-unidirectionally reinforced fabric show significantly smaller damping values than the plain-weave and twill-weave fabric. In detail the 0°-unidirectionally reinforced laminate of UD-strands shows the smallest damping. In contrast, the plain-weave fabric shows the highest damping, whereas the twill-weave fabric only shows a slightly smaller damping. The effect, however, is lead back to friction, what is rather improbable when the specimens originally are neither prestressed nor damaged.

Guan 1997 [16] carries out FE-calculations in order to investigate the visco-elastic damping in fibre reinforced plastics with fabric reinforcement. Thereby, the modelling of a representative volume element of a glass fibre reinforced thermoset (matrix system: vinyl ester) with plain-weave reinforcement is focused in the calculations. Photomicrographs are prepared and investigated by microscopy, in order to experimentally determine the mesomechanic geometry. In order to validate the FE-calculations the free-decay of vibrations of flat beam-like specimens, excited by mechanical impulse, are measured. The results correlate with two analytical models. The sensitivity of the analytical model to the fibre volume content and the length of the ondulation due to the fabric reinforcement is investigated with the objective to optimize the material damping in fibre reinforced plastics. Regarding the geometry of the ondulation another sensitivity analysis regarding the length of the ondulation is carried out. However, the results show, that the material damping is relatively insensitive to the variation of this geometric parameter, at least in the considered range of the parameter variation of the length.

Nakanishi et al. 2007 [42] investigate damping properties of fibre reinforced plastics with fabric reinforced single layers. In this case plain-weave fabrics of glass fibres with vinyl ester as the polymeric matrix system are focused. Therefore, FE-calculations are carried out, that are validated by experimental results. The FE-calculations are carried out with three-dimensional, heterogeneous elements, so-called representative volume elements. Thereby, the impregnated rovings of the reinforcement fibres are presumed as unidirectionally reinforced, and thereby presumed as transversal isotropic in the macroscopic scale, whereat the material properties follow the shape of the ondulation. The surrounding matrix is presumed as isotropic in the macroscopic scale. The structural mechanical material properties of the unidirectionally reinforced regions of the warp and fill yarn are determined by rules of mixtures. The underlied fibre volume content is determined experimentally by the evaluation of photomicrographs by laser-microscopy and a digital postprocessing. The experimental results show the highest dynamic stiffnesses for an orientation of the fabric reinforcement in 0°- and 90°-direction, respectively, whereas the orientations in ±45° show the lowest values. The determined material damping behaves oppositely to this correlation. It shows the lowest values in 0°- and 90°-direction, respectively, whereas the orientations in ±45° shows the highest values. The results of the simulation follow the indicated experimentally determined structural mechanical properties regarding natural frequencies a corresponding material damping.

Kreikmeier et al. 2011 [28] carry out analytical and numerical investigations of carbon fibre reinforced plastics with defects definitely caused by the manufacturing or production process. Two aspects are considered as defects conditional of manufacturing. These are first the so-called fibre-crimp in longitudinal direction in the plane of a single layer and second the voids in the laminate. The investigations are carried out against the background of the increased application of resin transfer moulding or vacuum infusion processing production processes and its time and cost advantages compared to the autoclave processing. In contrast to the compaction of the single layers and thereby of the laminate due to the applied pressure in autoclave processing, misaligns as relative displacements between the single layers can occur in the injection based production processes. Thereby, the final orientation of the fibres differs from the desired one, as illustrated in Fig. 11.

Photomicrographs over the thickness of the laminate show, that the afore described crimp occurs in the direction of the thickness of the laminate. Thereby, the single layers with more intensive crimp are located in the inner of the laminate, whereas at the outer sides the crimp is distinctly less intensive and partially not visible at all. This effect is lead back to the influence of the form or mould on the outer layers. The influence of the crimp of the fibres in the dimension of the thickness as defects conditional of manufacturing due to the injection based production processes on the stiffnesses and strengths is investigated analytically, based on a representative volume element. Thereby, the shape of an uniform crimp of the fibre is presumed as sine-shaped as a simplifying approach. In the carried out FE-calculations the term ratio of waviness or crimp is used for the first time. It is defined as the ratio of the amplitude A to the length of the waviness or crimp L by

A/*L*. The degree of waviness is varied in a range of < 0.1 to 0.2. In case of the considered maximum value *A*/*L*=0.2, the relative change of the (quasi-)static structural mechanical stiffness based on the ideally 0°-unidirectionally reinforced material. Whereas the longitudinal stiffness increases, the transversal stiffnesses as well as all three shear-stiffnesses increase, too. Thereby, an increasing degree of waviness causes an increasing stiffening in longitudinal direction as well as in transversal direction.

Guan and Gibson 2001 [17] carry out analytical, numerical and experimental investigations in order to describe the structural dynamic damping mechanisms in the mesomechanic scale. The analytical approach and the numerical FE-calculations are based on the geometry of a plain-weave fabric, whereat one representative element is considered at a time. The actual plain-weave unit cell and the step-by-step FE-modelling from the ondulating yarns to the regions of the surrounding pure matrix is illustrated in Fig. 12. Based on the strain-energy-method the single loss-factors are calculated. In the experimental investigations a plain-weave fabric reinforced glass fibre with vinyl ester as the matrix material is characterized by the method of impulse and resulting frequency response. The analytical model is based on the so-called mosaic-model according to Ishikawa and Chou 1983 [24], as illustrated in Fig. 13. It idealizes the ondulation by connecting discrete prismatic sequences, that are 0°- and 90°-unidirectionally reinforced, to an asymmetric cross-ply laminate. This fact enables the application of the classical lamination theory and the elastic-visco-elastic correspondence principle. In contrast to the analytical mosaic-model, the FE-calculations consider a continuously differentiable ondulation of a relatively coarse fabric, i. e. with high thickness with high areal weight.

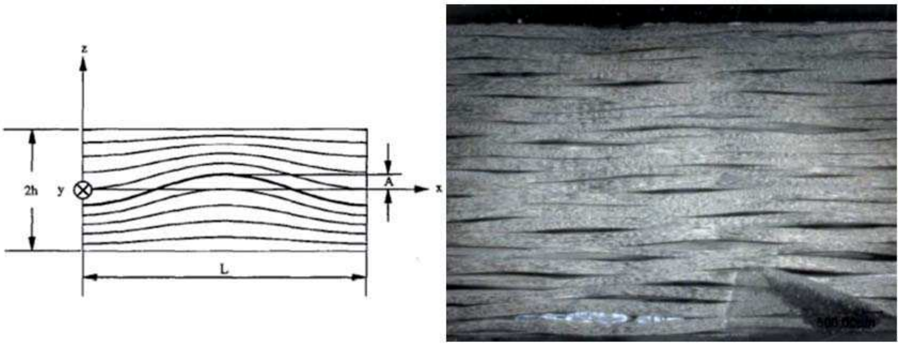


Fig. 11. Mechanical model of a gradual misalign over the thickness direction and corresponding photomicrograph [28]

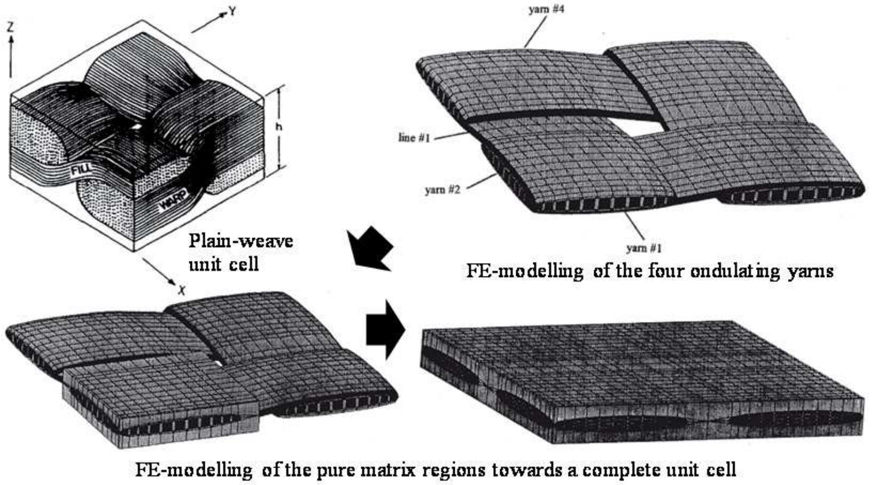


Fig. 12. Plain-weave unit cell [14] and corresponding FE-modelling from the ondulating yarns to the regions of the surrounding pure matrix [17]

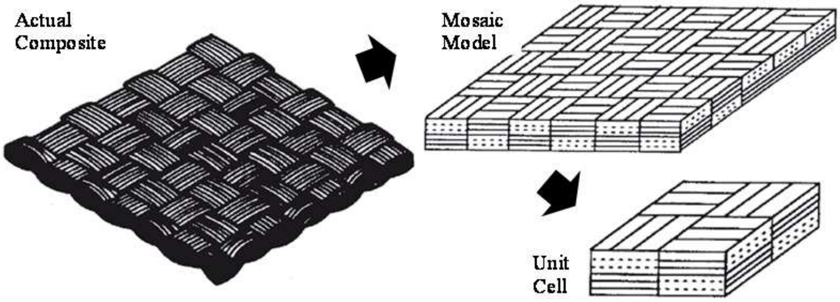


Fig. 13. Mosaic model connecting discrete 0°-/90°-sequences [24]

The loss-factors as a degree of the material damping are calculated according to Ungar and Kervin 1962 [60], who proof that for arbitrary systems of linear visco-elastic elements the loss-factor of the systems is the ratio of the sum of the products of the single element loss-factors and the total strain-energy stored in the element. The experimental investigations consider the free-decay of transversal vibrations of a cantilever. The excitation in both cases is done by an electro-magnetic hammer and the measurement of the transversal vibration is done by an eddy current sensor. Regarding the loss-factor of the reinforcement fibres and the fibre volume content in the impregnated rovings a sensitivity analysis has been carried out. At decreasing loss-factors of the reinforcement fibres the loss-factors of the composite material decrease, too. Analogue, the loss-factors of the composite material increase at increasing fibre volume contents in the impregnated roving. A sensitivity analysis of the determined loss-factors by the FE-model regarding the number of elements in the FE-model shows, that an increase of the number of elements only slightly influences the obtained results. Finally, it is stated, that the results of both the analytical modal and the FE-calculations can be improved by presuming a lower loss-factor of the reinforcement fibres and/or an increased fibre volume content of the impregnated rovings. However, the results of the analytical model with its strongly simplifying presumptions by the prismatic, discretely reinforced mosaic-model, that does not describe continuously differentiable ondulations, do not differ strongly from the ones of the FE-model, that represents the geometry significantly more precise and realistically. This effect is lead back to the property of the strain-energy, that is calculated by integration over one volume.

Matsuda et al. 2007 [31] present FE-calculations regarding the elastic-viscoplastic behaviour of plain-weave fabric glass fibre reinforced plastics and its validation by tensile tests. A case-by-case analysis regarding the arrangement of the single layers to each other is carried out. In detail these are the two cases of “in-phase”- and “out-of-phase” arrangement of two adjacent single layers in a laminate, as illustrated in Fig. 14 left. Both configurations are mentioned in [17], too, but not considered further. The rovings are presumed as unidirectionally reinforced, transversal isotropic, regions with a modelled linear-elastic material behaviour. The surrounding matrix is presumed as isotropic and modelled with an elastic-viscoplastic material behaviour. The calculation of the material properties of the unidirectionally reinforced impregnated rovings is done by homogenization approaches or so-called rules of mixtures. Therefore, a fibre volume content of φ_f=75% has been assumed. The value has been determined by the evaluation of photomicrographs by microscopy, where for a dominant part a hexagonal array of the monofilaments has been identified. The relatively high fibre volume content has already been used in the preceding work of Matsuda et al. [32]. In order to validate the results of the FE-calculations, specimens of plain-weave glass fibre reinforced epoxy are investigated by experimental tensile tests. Thereby, a total of four different kinds of layups are investigated, whereat the angles of the predominant direction are varied from 0° to 45° in steps of 15°. The validation is shown in Fig. 14 right. The global strains have been measured by resistance strain gauges. The experimentally determined mechanical stress-strain-diagrams are compared to them of the two kinds of arrangement of the case-by-case analysis. The 0°-reinforced specimens, i.e reinforced in warp direction, nearly show linear-elastic stress-strain-diagrams. The linearity strongly decreases with the increasing angles in steps of 15° from 15° to 45°. The resulting non-linear stress-strain-diagrams are caused by the increasing influence of the elastic-viscoplastic epoxy resin. Thereby, the results of the FE-calculations agree relatively well with the experimentally determined results. The results of two kinds of arrangement of the case-by-case analysis, “in-phase” and “out-of-phase”, considered in the FE-analysis, basically do not differ in the elastic range. Only in the visco-plastic range the in-phase arrangement shows slightly higher stresses than the out-of-phase arrangement in case of the orientations from 15° to 45°. Solely in case of the 0°-orientation the out-of-phase arrangement shows higher values of the stresses than the in-phase arrangement. Depending on the two kinds of arrangement a respective approach for the homogenization as a rule of mixture is indicated.

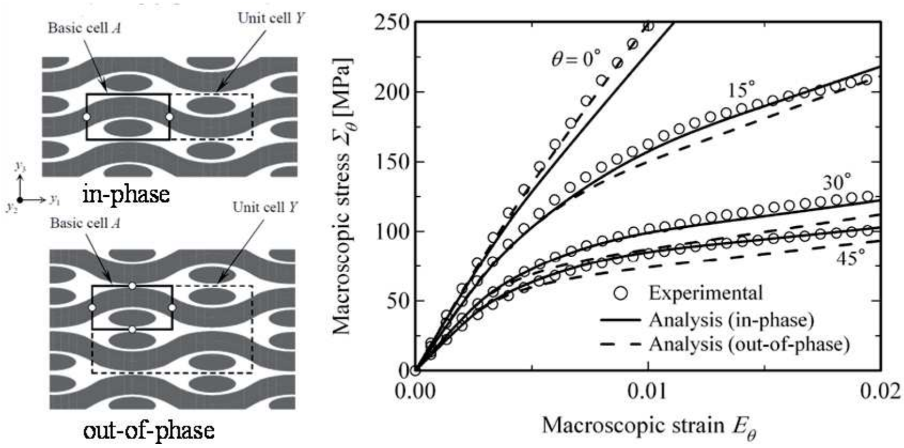


Fig. 14. In-phase and out-of-phase configuration of the unit cell (left) and experimental and numerical results (right) [31]

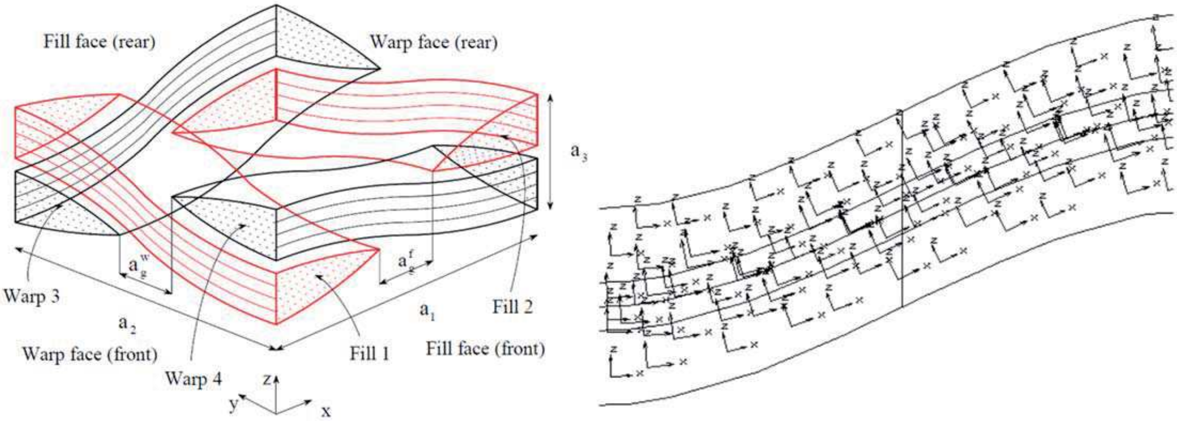


Fig. 15. Parametric geometry of a plain-weave (left) and element coordinate systems along the roving contour (right) [4]

Barbero et al. 2006 [4] describe a FE-model for the calculation of laminates of plain-weave reinforced single layers. For validation issues the results of experimental investigations reported by three cited papers have been used. They contain considerations of plain-weave reinforced single layers as well as the case-by-case analysis regarding the in-phase and out-of-phase arrangement of adjacent single layers, analogue to [31]. In the description of the state of the art the existing approach of sine-shaped ondulations with sine-shaped or elliptic cross-sections of the single rovings according to Chou and Ito 1998 [12] is indicated. Additionally the mosaic-model according to Ishikawa and Chou 1983 [24] is presented. In contrast to analytically closed models, that yield simplified stress-strain-correlations, the numerical models yield much more detailed ones. It is noticed, that the fabric ondulations generally reduce the structural mechanical material properties in terms of stiffness and strength. Representative elements, based on photomicrographs investigated by microscopy, are modelled further, as illustrated in Fig. 15

left. The evaluation of the photomicrographs essentially yields a sine-shaped centre-line as well as sine-shaped cross-sections of the single rovings. The rovings are modelled with transversal isotropic material behaviour. Thereby, it is important that the element coordinate systems follow the contour of the single ondulated rovings, in order to represent the orientated material properties, as shown in Fig. 15 right. Regarding the fibre volume content the fibre reinforced regions and the regions of pure matrix without fibre reinforcement are considered. Thereby, the knowledge of the fibre volume content of the fibre reinforced regions is relevant for the calculation of the structural mechanical material properties by micro-mechanical homogenization theories, whereat this value is not determinable experimentally. Actually, the experimental determination of the fibre volume content yields the value of the entire RVE in terms of a global fibre volume content. Therefore, the fibre volume content in the fibre reinforced regions is calculated by the relation of the fibre reinforced region or volume to the entire region or volume. In this case the procedure is named “volume correction”. From this follows, that laminates of arbitrary kind of fabric reinforcement the fibre volume content of the rovings is always higher than the experimentally determined value. For simplifying issues, regions of pure matrix without fibre reinforcement are presumed as completely filled with matrix. The presented method shows the correlation between local and global fibre volume content.

The review of Ansar, Xinwei and Chouwei 2011 [1] mainly treats three-dimensionally reinforced composites. However, certain sections are relevant regarding the modelling of fabrics as two-dimensional textile semi-finished products, because therein mesomechanic correlations are described. For a selected range of geometric parameters of the rovings Wu 2009 [64] gives a tabular overview. Thereby for a distinct geometric description of the textile semi-finished product the relevant parameters are the form of the cross-section, the course and the position of the single rovings. Based on the physical value of the density of the material of the monofilaments the linear density of the roving follows. The thickness and the width of the rovings can be determined experimentally, the local and the global fibre volume content and the thickness of the textile semi-finished product are additional characteristic parameters. Together with the number of non-ondulated rovings in a single layer and the number of warp and fill yarns per unit length of a single layer the distinct characterization of a fabric reinforced single layer is possible. Based on the afore described parameters, the global fibre volume content, the areal weight or grammage, and relation of the volumes of the crossing rovings follow. During the further procedure the different shapes of the cross-sections of the rovings are considered. In different papers for simplifying issues partially elliptic, lenticular, rectangular, circular or racetrack-shaped cross-sections are presumed. With the knowledge of the shape of the cross-section and the characteristic geometric dimensions the resulting fibre volume content can be calculated. In case of the micromechanical consideration of the single monofilaments in surrounding matrix this is done by the ratio of the areas of the cross-sections. In this context Buchanan et al. 2009 [7] indicates the maximum of the theoretically achievable fibre volume content under the presumption of circular-shaped cross-sections of the reinforcement fibres with constant diameter. Thereby, two basically different ideal arrays exist. These are the square edge or quadratic packing and the hexagonal packing. In case of the maximum density of the packing array, the cross-sections of the single monofilaments get in point contact to each other. The maximum values are $\varphi_{\mathrm{f,max,qp}}=\pi/4\approx78.5\%$ and $\varphi_{\mathrm{f,max,hp}}=\pi/\left(2\sqrt{3}\right)\approx90.7\%$. During the further procedure the relevant equations for the calculation of the geometric and volume relations for the modeling of single rovings are indicated. Finally, a tabular overview of the different analytical approaches regarding the shape of the ondulation for fabric reinforcements and different shapes of cross-sections of the rovings are indicated. Fig. 16 illustrates the two basic arrays of the single reinforcement fibres and relevant cross-sectional shapes of tows or rovings.

3. Comparison and remarks

Against the background of the cited and briefly presented papers there are some remarks and conclusions.

3.1. Micromechanics, fibre packing arrays and interpahse

In [1] and [7] the maximum value of the fibre volume content under the presumption of the maximum of the theoretically achievable fibre volume content under the presumption of circular-shaped cross-sections of the reinforcement fibres with constant diameter. These are the square edge or quadratic packing and the hexagonal packing with the corresponding maximum values $\varphi_{\mathrm{f,max,qp}}=\pi/4\approx78.5\%$ and $\varphi_{\mathrm{f,max,hp}}=\pi/\left(2\sqrt{3}\right)\approx90.7\%$.

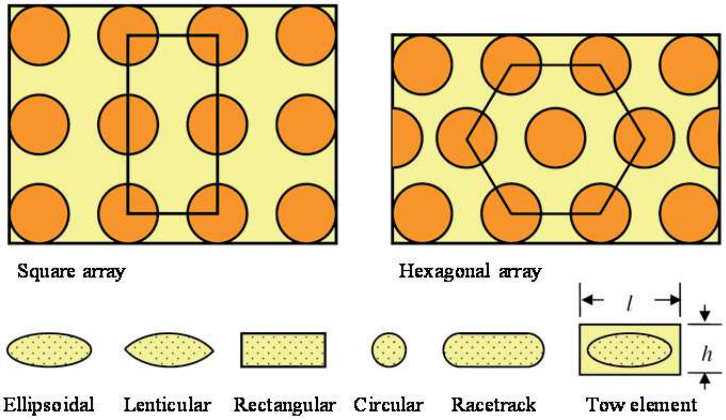


Fig. 16. Square and hexagonal array of single fibres (top) and cross-sectional shapes of tows or rovings (bottom) [1]

In [29] the interphase is identified to significantly influence the damping in fibre reinforced plastics. Additionally, therein and in [59] the influence of the micromechanical packing array of circular-shaped cross-sections of the reinforcement fibres with constant diameter are investigated, that influence the damping behaviour, too. However, the practicability and technical feasibility to influence the microscopic packing array is not considered in both cases. Thereby, usually a constant quality of the interphase and the structural integrity of the specimens is presumed, analogue to [62]. Additionally, regarding the micromechanical packing array it is usually implied, that there is a homogeneous distribution of the reinforcement fibres or of the monofilaments. Further, even locally none of the two afore described maximum packing arrays occur, so that the structural mechanical material properties can be calculated by micromechanical homogenization approaches.

3.2. Mesomechanic geometry

In [17] the so-called mosaic-model according to [24] is described, that despite of modelling the ondulation in a non-continuously differentiable manner in the dimension of the thickness, yields good accordance with experimentally determined damping values. In contrast, in [28] the so-called fibre-crimp or fibre-waviness in longitudinal direction in the plane is modelled more realistically by trigonometric functions. Although this approach is not based on the description of fabric reinforced single layers, it can be used analogue for such. Thereby, the deviations of the reinforcement fibres are denominated defects conditional of manufacturing. This is not correct in case of fabric reinforced single layers, because the ondulation is caused by the geometry of the textile semi-finished product. In contrast to defects conditional of manufacturing, ondulations have to be considered as fibre-crimp or fibre-waviness in the dimension of the thickness, although these can be analytically described by the same approach, as represented in Ottawa et al. 2012 [43], Romano 2016 [46] and Romano et al. 2017 [47], analogue to Valentino et al. 2013 [61] and Valentino et al. 2014 [61]. However, the considered fibre crimp or waviness differs from typical ondulations in fabrics, because they are not caused by the crossing of warp and fill yarn. Geometric dimensions in the mesomechanic scale, mostly of plain-weave fabrics, as schematic illustrations or photo-micrographs are given amongst others in [2], [3], [4], [17] and [54], cf. Fig. 8 and Fig. 15. Thereby, mostly a fabric reinforced single layer of plain-weave fabric with $[(0/90)]_n$-orientation, i. e. in warp direction, is considered. In all considered papers there are simplifying presumptions regarding the geometrical relations and the structural mechanical material properties of the resulting different regions. Whereas the presumptions regarding the meso-mechanical geometry partially differ from each other, the presumptions regarding the structural mechanical properties nearly always are similar. The ondulated impregnated rovings are always presumed as ideally parallel unidirectionally reinforced, surrounded by regions of pure matrix without fibre reinforcement. In some papers besides the geometric relations additionally the relevant geometric dimensions are indicated. They are necessary for the distinct description of the geometry of the fabric ondulation as well as for the estimation of the realistic mesomechanic dimensions. None of the considered papers that present numerical FE-calculations, mention the problematic positions regarding the meshing, where slight modification of the geometry are necessary. These are amongst others the edges of the acute angles of the sine-shaped or lens-shaped cross-sections.

3.3. Degree of ondulation

In [16] for the first time the effect of the variation of the geometric parameter of the length of an ondulation is considered by FE-calculations. In this case the results show, that the material damping is relatively insensitive to the variation of the length. However, the range of the variation in absolute and in relative terms is small. In the paper of the FE-calculations of [28] for the first time the term fibre-crimp or fibre-waviness is used. It is defined as the relation of amplitude A and length L by A/L, but no formula symbol is introduced, and the background for the definition is not explained. It is indicated, that in the FE-calculations the values of the fibre-waviness have been varied in the range of < 0.1 to 0.2, but no graphical illustrations of the results are provided. The results of the (quasi-)static calculations show, that at the considered maximum of $A/L=0.2$ the stiffness in longitudinal direction increases significantly. This effect can eventually lead back to the distinctly lower stiffness of the surrounding matrix, and thus to the absent effect of support by the perpendicularly orientated fill yarns. The stiffness perpendicular to it as well as all three shear-stiffnesses behave contrarily and increase. The results are explained by an enhancing stiffening effect in direction of the thickness at an increasing ratio of fibre-crimp or waviness. However, the explanation of the FE-calculations does not contain the applied ranges of displacements or strain, for which this behaviour has been identified.

Although in [28] instead of fabric ondulations the fibre-crimp or waviness in longitudinal direction in the plane as defects conditional of manufacturing are considered, the thoughts can be adopted for the consideration of fabric ondulations. Therefore, the wave steepness S used in nautics, as exemplarily defined in Büsching 2001 [8] is modified. It is $S=H/L$, where $H=2A$ is the absolute wave height in terms of twice the amplitude A and L is the length,. However, due to the different motivations, necessities and intentions of the respective subject area a modification is required, when fabric reinforced composites are considered. In nautics it is important to characterize the absolute load a structure undergoes during its life-cycle, e. g. regarding fatigue strength issues. Therefore, twice the amplitude A corresponding to the absolute wave height H is considered in the calculation of the specific value S [8].

In contrast, when fabric reinforced composites are considered, the characterization of the deviation from the ideally orientated unidirectionally reinforced single layer caused by the ondulation in the fabric is focused [54]. The modification towards considering the single value of the amplitude A must then be interpreted as a degree of eccentricity compared to an unidirectionally reinforced single layer, that exhibits an ideally orientated reinforcement without ondulations. Based on the original thoughts of Kreikmeier et al. 2011 [28] and the wave steepness in nautics [8], this yields the definition of the degree of ondulation $\tilde{O}=A/L$ introduced in Romano 2016 [46] and Romano, Ehrlich and Gebbeken 2017 [47] as the relation of the amplitude A to the length of the ondulation L. The non-dimensional specific value $\tilde{O}$ thus represents the rate of intensity of the continuously differentiable presumed geometric direction change of the ondulation.

3.4. Mesomechanic kinematic

The acting of the structural mechanic damping mechanism in fabric reinforced single layers of fibre reinforced plastics is explicitly mentioned in [14], but not treated further. Although therein only specimens with layups of fabric reinforced single layers are investigated by structural dynamic experiments, possible effects acting in the mesomechanic scale, and could thereby be interpreted as damping enhancing material couplings, are not considered further. In [6] regarding an assumed damping enhancing effect in fabric reinforced single layers [44] is referenced, where a first analytical approach is given by the so-called fabric-geometry-model (FGM). In [13] the material damping in fibre reinforced plastics with different textile semi-finished products impregnated with the same polymeric matrix system is investigated. Thereby, at the same predominant direction the values of the material damping differ significantly. The 0°-unidirectionally reinforced laminate of UD-strands and the 0°-unidirectionally reinforced fabric show significantly smaller damping values than the plain-weave and twill-weave fabric. This is explained by energy-dissipating friction-effects or relative displacements between warp and fill yarns. Because in case of carefully produced materials and undamaged specimens, however a sufficiently good impregnation of the fabric and thus a sufficiently high fibre-matrix-adhesion can be assumed, this observation is a proof for additionally dissipated energy at the free-decay of vibrations, that can be lead back to the repeated acting of a mesomechanic kinematic due to geometric constraints in fabric reinforced single layers. Simple analytical approaches based on the method of the investigation of the strain-energy under the simplifying presumption of plane stress are no longer suitable for the description of the actually three-dimensionally acting effect.

Extended numerical investigations, taking in consideration three-dimensional effects of acting strains and resulting stresses under the application of selected deformations are presented in Valentino et al. 2013 [61] and Valentino et al. 2014 [61]. A reduced two-dimensional but parametric model is investigated and validated in Ottawa et al. [43]. The achieved results are developed further and extended by analytical considerations in Romano 2016 [46] and Romano, Ehrlich and Gebbeken 2017 [47], wherein a mesomechanic acting principle is presented and identified. Plain representative sequences of balanced plain-weave fabric reinforced single layers based on sines are considered. Thereby, the variable geometric parameters are the amplitude A and the length L of the ondulation. For further parametric and non-dimensional considerations it is convenient to introduce the degree of ondulation $\tilde{O}=A/L$ [46], [47]. In the carried out FE-calculations of [43], [46] and [47] a plain strain state is presumed for plain representative sequences of one complete ondulation. Selected longitudinal deformations are applied on the plain sequences, and the linearly-elastic response in the through-thickness direction is evaluated. In order to achieve qualitative correlations the geometric dimensions and the applied deformations are varied in selected steps. In detail the structural mechanical material properties are varied parametrically and a required case-by-case analysis regarding the boundary conditions on the horizontal edges is considered. In the evaluation of the results the elastic part and the part of the mesomechanic kinematic due to geometric constraints are separated from each other. Finally it is shown, that the intensity of the can be expressed in terms of the introduced degree of ondulation $\tilde{O}$ in fabric-reinforced single-layers.

In detail two different effects in the model can be identified, when positive and negative longitudinal deformations are considered. In both cases the unidirectionally reinforced ondulated yarn is subjected to a purely elastic deformation. Additionally at the same time in case of positive longitudinal deformations a smoothing or flattening, and in case of negative deformations an upsetting of the unidirectionally reinforced ondulated yarn is induced due to its ondulated shape. In both cases the variation of the amplitude is a superposition of transversal deformation due to Poisson effects as a purely elastic response and a purely kinematic response due to geometric constraints in the mesomechanic scale. In contrast longitudinal deformations applied on a unidirectionally reinforced single layer in direction of the reinforcement leads to a lengthening and shortening in longitudinal direction and a transversal contraction directly coupled due to Poisson effects only. The mesomechanic kinematic can be observed in both the analytic model and the FE-analyses [46], [47]. The analytic model yields hyperbolic correlations due to the strongly simplifying presumptions that neglect elasticity. In contrast the FE-analyses yield linear correlations in much smaller amounts due to the consideration of elastic parts, yet distinctly.

The analytical and numerical results of [43], [46] and [47] are basically validated in flexural vibration tests with flat beam-like specimens of fibre reinforced epoxy with 0°-unidirectional reinforcement and with fabric reinforcement in warp direction, as described in [43], [46], [48], [49]. The repeated acting of this mesomechanic kinematic due to geometric constraints is presumed to enhance the damping properties of fabric reinforced single layers compared to unidirectionally reinforced ones. For an evaluation the free-decay behaviour of flat beam-like specimens with fabric and unidirectionally reinforced single layers can be considered. Thereby the fixed-free boundary condition has been identified as adequate. During the free decay the structure undergoes the kinematic in a number of cycles equal to the fundamental frequency.

In detail the basic concept and the identification of the acting mechanism has been validated basically in Ottawa et al. 2012 [43] for one set of comparable specimens of basalt fibre reinforced epoxy (0° unidirectionally and 0° twill fabric 2/2 reinforced in warp direction). A more detailed validation of [47] is presented in Romano et al. 2014 [48], [49] and Romano 2016 [46] for three sets of comparable specimens of carbon fibre reinforced epoxy (0° unidirectionally and 0° plain and twill fabric 2/2 reinforced in warp direction).

3.5. FE-calculations

In [17] the FE-modelling of single impregnated rovings in representative elements of fabric reinforced single layers is treated. They are considered as rovings impregnated with resin. In reality the rovings consist of several thousands of monofilaments. For a simplified modelling the impregnated rovings are considered as unidirectionally reinforced regions, where the reinforcement fibres, and thereby the predominant direction, follows the shape of the ondulation. In [31] the idealized case-by-case analysis of the arrangement of two adjacent fabric reinforced single layers in-phase and out-of-phase is considered, and the problem is described, that representative elements considered by FE-calculations are not existent according to its idealized presumed form in real laminates. In the case of the in-phase arrangement the maxima of the warp yarns of the lower ply are located over the minima of the fill yarns of the upper ply and vice versa. In contrast, in case of the out-of-phase arrangement the maxima of the warp yarns of the lower ply are located over the minima of the warp yarn of the upper ply. Depending on the respective case of arrangement a representative volume element can be identified. Whereas in case of the in-phase arrangement it corresponds to the classical RVE of a plain-weave fabric reinforced plastic, in case of the out-of-phase arrangement a RVE consists of two adjacent and dephased RVEs. However, in reality none of the two idealized cases of arrangement will occur. Because of the transversal flexibility of the single rovings, the shear compliance of the fabric and the tendency of the rovings to slip into the gaps, the ondulated rovings of the two adjacent upper and lower plies finally will be located in or near the gaps. A surrounding matrix is modelled in the RVEs, that will not develop in reality, too. This is descriptively proved by photomicrographs of laminates of fabrics of different kinds of reinforcement fibres or different kinds of fabric constructions, that have been produced by autoclave processing.

3.6. Global and local fibre volume content

In Matsuda et al. 2007 [31] for the impregnated rovings of a representative element a relatively high fibre volume content of φ_f=75% is presumed. The value of the fibre volume content has been identified from photomicrographs by microscopy, and the dominantly identified hexagonal packing array of the monofilaments. This relatively high fibre volume content has already been used in a previous paper of Matsuda et al. 2002 [32]. In [4] the fibre reinforced regions of the impregnated rovings and the regions of pure matrix without fibre reinforcement are considered in detail as the basically different regions of a representative element. Because the surrounding matrix reduces the fibre volume content of the entire representative element, there is a case-by-case analysis regarding the local fibre volume content of the impregnated roving and the global fibre volume content of the entire representative element. The local fibre volume content in the fibre reinforced rovings is relevant for the calculation of the structural mechanical material properties by micromechanical rules of mixtures. However, the local fibre volume content is not directly determinable experimentally, because an experimental determination of the fibre volume content always yields the fibre volume content of the entire RVE as the global value. Therefore, in Barbero 2006 [4] and 1995 [5] the calculation of the local fibre volume content is done by the so-called “volume correction”, that is based on the relation of the fibre reinforced volume to the entire volume of the RVE. It is emphasized, that by means of an experimentally determination of the fibre volume content only the overall value can be obtained. Standardized experimental methods for determining the fibre volume content are for example the German standards DIN EN 2564 [38] regarding (wet-) chemical extraction of organic reinforcement fibres and DIN EN ISO 1172 [39] regarding thermal extraction of inorganic reinforcement fibres. The experimentally determined values of specimens cut out of test panels built up of fabric reinforced single layers have to be considered consequently as the overall value of the fibre volume content. Because the two basically different kinds of arrangements presented in [31] do not exist in reality, and the mesomechanic regions of pure matrix are significantly smaller, the differences between the global and the local fibre volume content are significantly smaller, too.

3.7. Flexural vibration test

In many of the considered papers, as exemplarily [13], [16], [17], [27], [36], [42], [50], [51], [52], [53], [55] and [58], the flexural vibration test of flat beam-like specimens is indicated as a suited experimental method for the identification of the structural mechanical material properties. At small amplitudes, and thereby at small stress levels, hysteric damping and viscous damping correspond. Further, the flexural vibration test is suitable especially because of its large range of linear damping behaviour, that enables the experimental determination of the material damping for the validation of results of analytical and/or numerical investigations. In addition, the flexural vibration test is standardized as experimental method for the determination of structural dynamical material properties in the DIN EN ISO 6721 of 1996 [40], that replaces the drawn back DIN 53440 of 1984 [37].

3.8. Parameter of the experimental structural dynamic investigations

Regarding a representative evaluation of the experimental structural dynamic investigations has to be comparable. In [52] and [53] the sensitivity of the results on the amplitude and on the duration of the evaluated period of the flexural vibration test is considered. In detail the experimental investigations have been carried out at three differently strong exciting frequencies over a shorter and a longer evaluated period (10 and 50 cycles). In contrast to the evaluated stiffnesses the determined damping values strongly depend on the respective frequency and on the amplitude of the vibration. Thereby, at increasing amplitude of the vibration the measured material damping increases. The shorter evaluated period of 10 cycles yields higher damping values by trend than the longer evaluated period of 50 cycles. The reasons therefore are the geometric and/or physical non-linearities, that have to be avoided or reduced down to a constant minimum, so that the evaluated structural dynamic material properties can be considered as linear visco-elastic values.

3.9. Evaluation of the results

The rejection of initial ranges of the evaluated period of the measurement assures that inhomogeneous parts of the vibration at the beginning are not considered, but only the harmonic vibrations in the homogenous state are evaluated. Regarding the evaluation of the experimental structural dynamic investigations it is considered in [52] and [53] to determine the damping at low frequencies by the free-decay of the vibration in the time-domain, and only at high frequencies to determine it by the half power bandwidth method in the frequency-domain. The determination of the dynamic modulus E^* in terms of the storage modulus E' and the loss modulus E'' by the natural frequency and the material damping, determined by the evaluation of the recorded signal in the time-domain at given physical material properties density, geometric dimensions of the cross-section and the unsupported length is carried out for example in Romano et al. 2014 [48], [49], Romano 2016 [46] and applied analogue to [50] and [51].

3.10. Validation

Of the considered papers especially [13], [15], [16], [17], [25], [27], [42], [50], [51], [55] and [62] contain numerical investigations by the FE-analysis together with the validation of its results by experimental structural dynamic investigations, whereas other papers contain either experimental, numerical or analytical results, only. As presented in [11], the different damping mechanisms in fibre reinforced plastics act coupled and at the same time. Therefore, the phenomenological determination of the material damping is used for the experimental structural dynamic investigation of flat beam-like specimens in the flexural vibration test. A detailed distinction of the different damping mechanisms, that occur coupled and at the same time, is thereby only possible under high effort, and mostly neither necessary. The method of comparing measurements of geometrically similar specimens (regarding the dimensions of its cross-sections) with only different kinds of fibre reinforcement (unidirectionally and fabric reinforced) under the presumption different constant conditions (for example under constant geometric conditions, i. e. at same unsupported lengths, and under constant dynamic conditions, i. e. at the same natural frequencies) allows to presume as constant and thereby to neglect and to eliminate the parameters, that cannot be assigned to the kind of fibre reinforcement. The procedure is applied analog in Romano et al. 2014 [48], [49], Romano 2016 [46] and Romano, Ehrlich and Gebbeken 2017 [47].

3.11. Reproducibility and sensitivity

Regarding a statistically firm evaluation, the reproducibility and the determination of the sensitivity of the results to different parameters of the experimental structural dynamic investigations, relevant aspects are illustrated amongst others in [13], [50], [51], [52] and [53]. The proof of reproducibility and a corresponding sensitivity analysis and parameter identification, with experimental structural dynamic investigations of flat beam-like specimens is reported analog in Romano et al. 2014 [48], [49], Romano 2016 [46] and Romano, Ehrlich and Gebbeken 2017 [47].

4. Conclusions and outlook

The conclusions of the reviewed papers regarding analytical and numerical investigations in the meso-mechanic scale as well as the results of experimental structural dynamic investigations in the macroscopic scale are summarized, and an outlook is given.

4.1. Conclusions

Relevant papers considering the structural mechanic material damping in fabric reinforced composites are presented and excerpted as a review. All of the papers have in common, that the considered characteristic mesomechanic geometries in fabric reinforced single layers distinctly affect the structural mechanical material behaviour.

The analytical and numerical investigations consider micromechanical issues, such as fibre packing arrays and interphase, as well as mesomechanical ones, as for example the geometry, the global and local fibre volume content and even first thoughts of a degree of ondulation. Thereby, the numerical investigations allow much more variations of parameters and a corresponding sensitivity analysis. Mostly three-dimensional representative volume elements (RVEs) are considered and evaluated amongst others by the strain-energy-method. However, thoughts of a mesomechanic kinematic in fabric reinforced single layers are not investigated in detail but partially mentioned.

The experimental validation of results of analytical and/or numerical investigations is usually carried out by experimental structural dynamic investigations. In detail the phenomenological determination of the material damping, partially including the aspects of reproducibility and sensitivity, is used for the experimental structural dynamic investigation of flat beam-like specimens in the flexural vibration test. This is probably the case because almost always the classic beam theory, i.e. shear-stiff kinematic of the cross-section, is implied. This assumption partially provides relatively simple governing differential equations at common boundary conditions (mostly fixed-free, i.e one sided clamped), when flexural vibrations are considered.

4.2. Outlook

In order to completely characterize the structural mechanic material damping in fabric reinforced composites further analytical and numerical investigations and especially their experimental validation are necessary.

Regarding further numerical investigations, it is suggested to carry out FE-calculations, including an identification of parameters and an analysis of the sensitivity of kinematic correlations due to geometric constraints acting in the mesomechanic scale. Therefore parametrical variations of geometric dimensions with the aim of identifying a kinematic coupling between longitudinal and transversal deformation could be focused. In detail plain representative sequences, analogue to Ottawa et al. 2012 [43], Romano 2016 [46] and Romano, Ehrlich and Gebbeken 2017 [47] and briefly introduced in Section 3.4, could parametrically be investigated further. Correlations regarding loading and displacements as well as deformations are relevant. This provides the basis for the identification of the influence of the kind of reinforcement fibre (glass, aramid, basalt compared to carbon) and of the kind of fabric construction (twill weave, satin weave (balanced and unbalanced) compared to commonly used plain weave) on the structural mesomechanic material behaviour of fabrics. The consideration of a linear visco-elastic material model instead of a linear-elastic material model, and the consideration of the sensitivity of the material behaviour on the kind of deformation (tension or compression) provide another expansion of the limits of the model conceptions. The expansion of the two-dimensional models to the third direction as the width or thickness of the (laminated) load bearing structures, respectively, provides a further extension for the consideration of surface structures.

The results of further investigations allow the conclusion that the presumed kinematic depends on meso-mechanic geometric dimensions. These purely geometric conditions can be stated in terms of a degree of ondulation, that represents the intensity of the single ondulated yarns in different kinds of fabrics (e. g. plain weave, twill weave, satin etc.). This consequently leads to the conclusion, that the degree of ondulation $\tilde{O}$, as introduced in Romano 2016 [46] and Romano, Ehrlich and Gebbeken 2017 [47] and briefly introduced in Section 3.3, should be considered in further investigations dealing with fabric reinforced composites and its structural mechanic material behaviour on the mesomechanic scale. Depending on the single case suitable modifications of this specific non-dimensional value are supposable, too. In each case it enables the comparability of analytic models and the results of numerical investigations. This is at the same time the requirement for a corresponding verification, where the degree of ondulation of fibre reinforced specimens can be determined by photomicrographs investigated by microscopy.

From the five different acting principles of structural dynamic material damping in fibre reinforced plastics classified and described in [11] only the first one is simply accessible. In research papers the second to fourth one are addressed more often, whereas the last one very rarely. In each case of the different damping mechanisms, that act coupled and occur at the same time, a separation is required in any case.

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