Chapter 15
Composite Process Chain Towards As-Built Design

Tobias Wille, Luise Kärger and Robert Hein

Abstract The relation between design and manufacture is of particular importance within the composite structure development process. Therefore, a continuous composite process chain beyond state-of-the-art is described in this section. Such an all-embracing process chain realizes a concurrent engineering, where iteration loops are enabled and, thus, product improvements and higher process efficiency are achieved. Concurrent engineering comprises the various interdisciplinary working phases and provides the necessary connectivity. In contrast to the traditional one-way relation from design to manufacture, the improved process chain also deals with the feedback from manufacture to design, based on numerical simulations. This is demonstrated by the example of composite parts made by Tailored Fiber Placement (TFP), including effects of the feedback on load bearing capacity.

15.1 Current State of Composite Processes

In spite of extensive effort within several research projects, the current development process of composite structures still exhibits a mostly sequential work flow, beginning with a first feasibility and concept phase, over the more detailed definition

T. Wille (✉) · R. Hein
Institute of Composite Structures and Adaptive Systems, German Aerospace Center (DLR e.V.), Lilienthalplatz 7, 38108, Braunschweig, Germany
e-mail: tobias.wille@dlr.de

R. Hein
e-mail: robert.hein@dlr.de

L. Kärger
Institute of Composite Structures and Adaptive Systems,
German Aerospace Center (DLR e.V.), Lilienthalplatz 7, 38108, Braunschweig, Germany

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Fig. 15.1 Sequential process chain of composites (state-of-the-art)

and development phase, the production and assembly phase up to the final phase of series production (Fig. 15.1). Several different methods and software tools are applied within these development phases in order to solve particular questions. Accompanying it, a heterogeneous set of tools with generally incomplete tool interfaces hinders a continuous development process with seamless interfaces. This directly affects process efficiency both short-term feasibility questions as well as comprehensive detailed design of composite structures. Therefore great potential could be tapped by a concurrent engineering approach, which may for example arise from an early feedback of manufacturing data to the design phase.

15.2 Continuous Composite Process Chain

Due to uncertainties during the production and assembly processes the structural capability of composites cannot fully be exploited within current composite design. In order to increase the performance of composite parts, the associated process steps were analyzed regarding their respective interdependencies and related exchange data. Aiming for a future "as-built" design process, which already includes all relevant production aspects beforehand, the development and the production phases have to be consolidated. Results of production process simulation and optimization are to be returned to the earlier development phase (Fig. 15.2). This feedback of process simulation data enables to take into account geometrical, material and process-induced deviations, such as local degradation of the composite stiffness and strength as well as manufacturing induced deformations and stresses. Hence, more precise and more robust prediction methods can be achieved and provide the basis for a less conservative dimensioning regarding weight reduction while assuring part quality at minimum process time. Therefore, an efficient and production conform preliminary design, a more reliable and comprehensive analysis as well as a time and cost efficient production shall be realized. These ambitious objectives are especially advantageous in view of high cadence processes, large components as well as complex assembly tasks of composites.

Within the continuous composite process chain many different composite manufacturing technologies, such as vacuum bagging, autoclave, and resin injection technologies as well as a great variety of derivatives and combinations of the aforementioned have to be considered [1]. Furthermore, the following main process steps are generally performed with high requested accurateness in order to accomplish the required composite part quality: tooling development (incl. heating and injection concept), draping/lay-up of woven or non-crimp fabrics (dry or pre-impregnated), resin injection (in case of dry fabrics) and curing (at elevated temperatures). With the

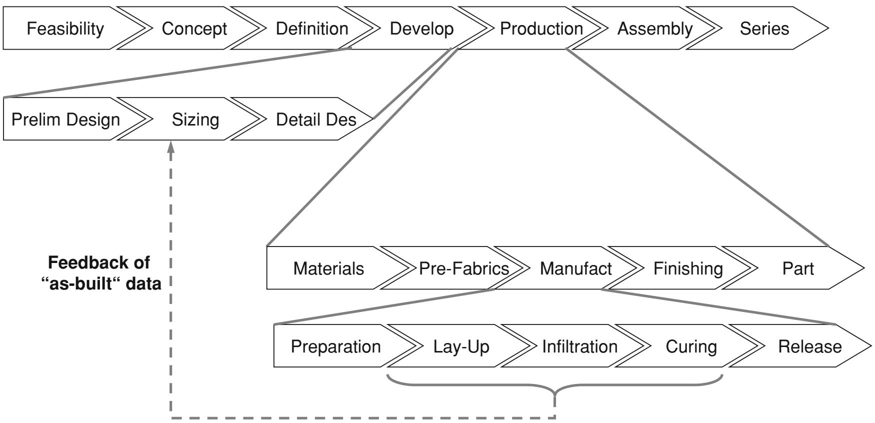

Fig. 15.2 Feedback of “as-built” data from the production phase to the earlier development phase within the continuous composite process chain

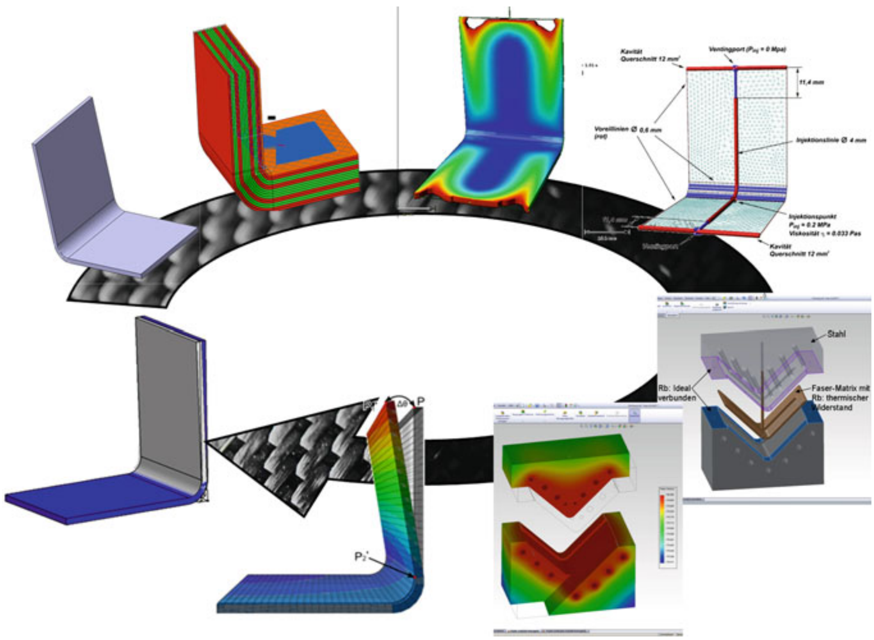

Fig. 15.3 Application of the continuous composite process chain to consider as-built information within the design phase

objective of an “as-built” composite part development, these process steps have to be analyzed regarding their effects on the composite part quality within the early development phase. For this purpose numerical process simulations are to be performed, and resulting data have to be returned into a more precise “as-built” component analysis via appropriate feedback algorithms. The example of a typical process flow depicted in Fig. 15.3 shall be described in more detail.

The starting point represents a mould with the desired dimensions. Considering the fabric lay-up process, draping, fiber placement or forming simulations can be accomplished, in order to receive spatially distributed geometric composite layer properties, such as fiber orientations, thickness distributions or shear angles. With respect to an optimal infusion concept, resin flow simulation can be used to predict flow fronts, dry spots or entrapments of air. Moreover, an optimal tooling and heating concept can be achieved by performing numerical heat transfer analyses coupled with mechanical analyses. Thus, thermal and mechanical boundary conditions can be provided for subsequent composite curing simulations. Since the actual composite properties are depending on the curing process, a prediction of spatially distributed exothermic reactions and degree of cure is of great interest. Furthermore, the process induced residual stresses and distortions, caused by chemical shrinkage and thermal expansion, can be received. These results are highly relevant with respect to a "first-time-right" part development and therefore need to be considered within the development phase. On one hand they can be transferred to Computer Aided Design (CAD) models in order to map/morph composite and tooling surfaces from a first nominal design to an "as-built" design. On the other hand residual stress fields can be integrated as initial loadings into the structural analysis, even superposed by impressed deformations (causing stress distributions) due to assembly, and therefore allow for a more realistic prediction of critical areas under operational loading conditions.

Since all these data are generally spatially distributed within the composite part, they have to be handled as relatively large field values, some of them even as a function of time. Specific aspects can already be handled by applying commercial software. For example, the main fiber direction can be transferred from draping simulation into the detailed finite element analysis. Also, temperature distributions, which were calculated within a tooling heat transfer analysis, can be imported as boundary conditions into a curing simulation. Even residual distortions can be mapped from curing and spring-in analysis onto the original part design. However, with respect to the multiplicity of phenomena, of simulations methods and of software systems, commercial software is currently not fully supporting all aspects of the composite tool chain.

15.3 Application of Manufacturing Feedback for Fiber Placement and Curing

Tailored or Advanced Fiber Placement (TFP or AFP) is a textile process for the production of optimized fiber reinforced structures. TFP follows the examples in nature, where an adapted, perfect design provides an optimal survive, cf. Mattheck et al. [2]. Accordingly, the carbon fiber rovings in TFP structures may be placed in

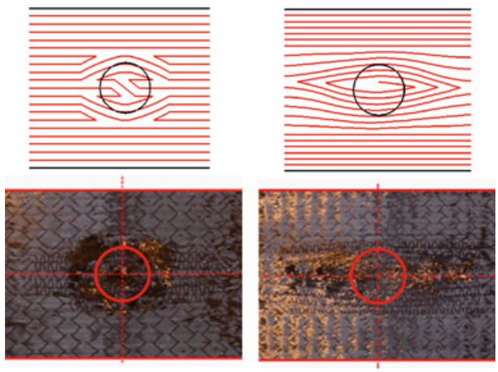

Fig. 15.4 TFP tension sample with a central open hole

almost any desired orientation, thus deploying calculated optimum fiber quantities and orientations for optimal performance [3]. However, the TFP manufacturing process also affects the material properties. Specific material properties and appropriate material models of the textile fiber composites are of critical importance for a successful application [4, 5].

To reliably predict the material and structural behavior, the TFP As-built Feedback Method has been developed. By means of this method, manufacturing data such as fiber alignments and effective global material properties of local fiber features (e.g. fiber turns) are suitably transformed to as-built finite element models. Consequently, high-fidelity Computer Aided Engineering (CAE) models are generated, which may significantly differ from the original CAE models used for design. Based on the accordingly improved analysis results, recommendations for enhanced design guidelines can be deduced.

Figure 15.4 shows an example, where it is clearly necessary to establish an as-built FE model instead of using the primary as-design FE model for certification: The TFP optimization provides a fiber alignment, which runs smoothly in a curvature around the hole. Since manufacturing constraints have to be considered, different solutions have to be evaluated to realize the curved fiber orientation: The left solution in Fig. 15.4 shows a TFP structure with constant fiber volume fraction, while the right solution shows a higher fiber volume fraction next to the hole. Since the failure behavior of these two examples will be different, various FE models are needed for an appropriate solution.

15.3.1 *Feedback of Effective Material Properties*

The first part of the TFP As-built Feedback Method embodies a Multiscale Analysis which considers local discontinuities and establishes a suitable

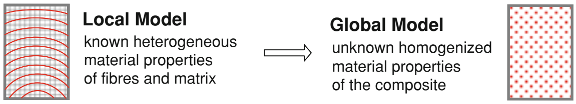

Fig. 15.5 First part of the feedback method: multiscale analysis

macroscopic resolution of material particularities (e.g. fiber turns, cf. Fig 15.5). Accordingly, suitable mesoscopic FE models (super-elements) are generated to precisely represent the real fiber alignment. Subsequently, the Asymptotic Homogenization Method (AHM) is applied to compute the effective macroscopic elasticity matrix. The AHM is a rigorous mathematical technique to predict the effective global properties of inhomogeneous media [6]. Coupled with the finite element method, the AHM has been supposed to be the most effective tool for the analysis of the microstructural effect on the global behavior of a composite material [7]. Accordingly, it is widely used in the field of composite and multi-scale research, it can be referred to e.g. Böhm [8], Chen et al. [9] and Hassani and Hinton [10, 11].

In the present work, the displacement method, as proposed e.g. by Lukkassen et al. [12], is applied to solve the cell problem of the AHM. By means of the displacement method, unit strain fields are introduced to the mesoscopic FE model (super-element). The corresponding boundary conditions are suchlike that points on opposite sites of the super-element are coupled to each other in all three translational directions except for one point, which is coupled only in two directions and in the third direction it moves by the length of the super-element. Figure 15.6 illustrates the reduction of the resulting effective stiffness component Q11 (stiffness in nominal fiber direction) depending on the radius of a fiber curvature: Q11 drops dramatically for increasing fiber curvatures, particularly if the curvature radius becomes smaller than the tenfold length of the super element.

The computation of effective strength components is build upon the so-called Direct Micromechanics Method (DMM), which was initially proposed by Zhu et al. [13]. Reduction of strength due to curvature is similar to the stiffness reduction shown in Fig. 15.6. The computed effective material properties, stiffness and strength, are transferred and used for the macroscopic as-built FE models.

15.3.2 Feedback of Fiber Alignment

Within the second part of the TFP As-built Feedback Method, the As-Design to As-Built Data Transformation is performed. Based on the preceding multiscale analysis, this transformation utilizes the effective global material properties. Furthermore, the actual fiber alignment of the manufactured structure, stored e.g. in Fiber Placement Manager (FPM) files, is automatically transformed into updated fiber orientations specified in the global FE model in Fig. 15.7.

In Fig. 15.7, the concept of the transformation from “as-design” (resultant model after optimization and conceptual sizing) to “as-built” (resultant model

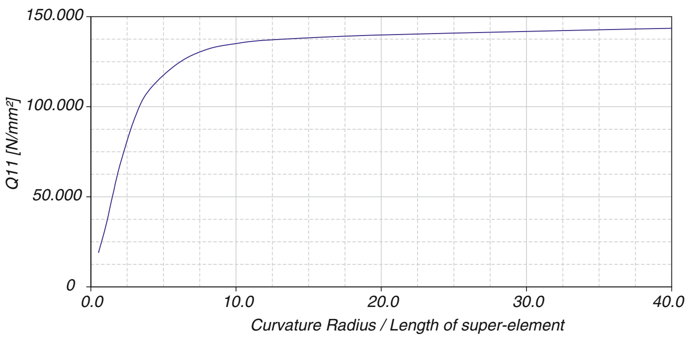

Fig. 15.6 Effective stiffness component *Q11* depending on the radius of fiber turns

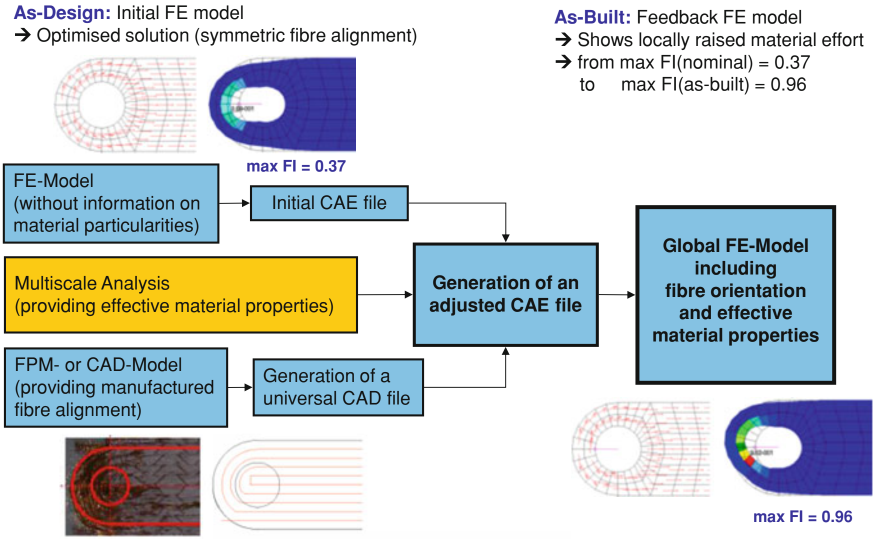

Fig. 15.7 As-design to as-built data transformation as one part of the TFP As-built Feedback Method: Reduction of load bearing capacity of a manufactured TFP tension strap compared to the initial design

from the TFP As-built Feedback Method) is illustrated using the example of a tension strap with two holes. The two contour plots show the computed material effort of the "as-design" (top left) and the "as-built" FE model (bottom right). The material effort is illustrated by the Failure Index FI which has been determined according to the Tsai-Wu failure criterion [14]

$$\mathrm{FI} = \left(\frac{1}{R_{1t}}+\frac{1}{R_{1c}}\right)\sigma_{11} + \left(\frac{1}{R_{2t}}+\frac{1}{R_{2c}}\right)\sigma_{22} - \frac{1}{R_{1t}R_{1c}}\sigma_{11}^2 - \frac{1}{R_{2t}R_{2c}}\sigma_{22}^2 + \left(\frac{1}{R_{12}}\right)^2\sigma_{12}^2,$$

where σ_{ij} are the stress components and $R_{1t}, R_{1c}, R_{2t}, R_{2c}, R_{12}$ are the strength components. The results show the reduction of load-bearing capacity: The optimization process provides a roving alignment, which runs smoothly in a curvature around the hole. For manufacturing, however, several constraints need to be considered, which result in unsymmetrical fiber alignments with local fiber particularities. Thus, the maximum failure index rises from FI (nominal) = 0.37 to FI (as-built) = 0.96 (i.e. close to damage at FI = 1). This signifies an alarming reduction of load-bearing capacity and thus, two important conclusions need to be drawn:

- It is certainly essential to consider the actual manufactured fiber alignment by an "as-built" FE model rather than analyzing the "as-design" FE model of a preliminary optimization process.
- For improved design and manufacturing guidelines, the negative effect of irregular fiber alignments must be considered. Hence, the communication from "as-built" FE analysis to the design and manufacturing departments is essential.

15.3.3 Feedback of Process Induced Residual Stresses and Distortions

Subsequent to the fiber placement process the curing process of composite parts takes place usually at elevated temperatures in heated toolings, ovens, autoclaves or alike. During curing the resin reacts exothermally, which may lead to inhomogeneous temperature distributions depending on the part thickness and on the applied heating concept. For that reason the final degree of cure may be varying spatially within the part, and thus, affecting the mechanical properties of the part. Additionally, chemical shrinkage takes place during curing, and thermal contraction occurs when cooling down the composite part to ambient temperature. Therefore, curing stresses build up, depending on both the thermal and mechanical boundary conditions as well as on the viscoelastic behavior of composites in rubbery and glassy state [1].

Within the last years several methods on curing simulation were published in order to predict both, the residual curing stresses and distortions of composites, e.g. White and Hahn [15], Karkanas and Partridge [16], Johnston [17], Svanberg [18], Ruiz and Trochu [19]. Aiming for a more realistic "as-built" design, these process induced preloads have to be transferred back to the earlier development phase. Accordingly, curing stresses and distortions can be considered as initial loading conditions when evaluating the component behavior under service loading conditions. Applying a coupled transient thermo-mechanical curing analysis, computation time can massively increase, which often limits the simulation of large composite parts. Therefore, it is advisable to consider more efficient

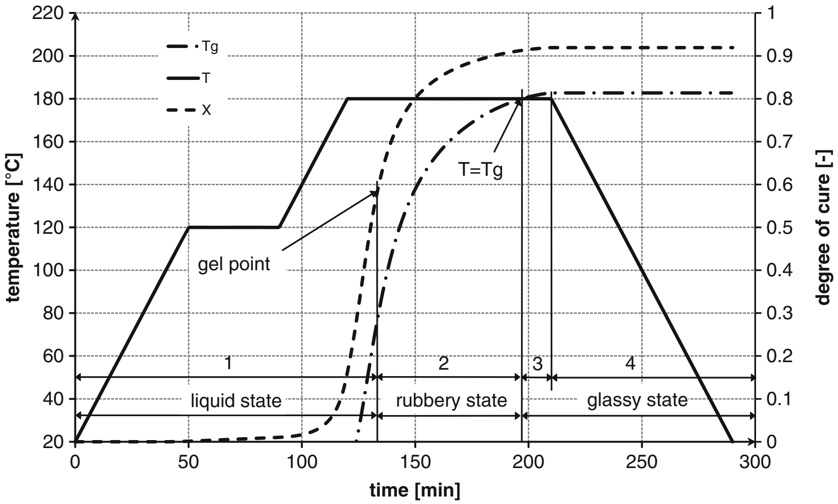

Fig. 15.8 Thermo-chemical simulation of degree of cure X and glass transition temperature Tg

Table 15.1 Steps during curing

Step	State	Effect
1	Before gelation	No effect on stress or distortion
2	Isothermal curing in rubbery state	Shrinkage
3	Isothermal curing in glassy state	Shrinkage
4	Non isothermal cooling in glassy state	Thermal expansion

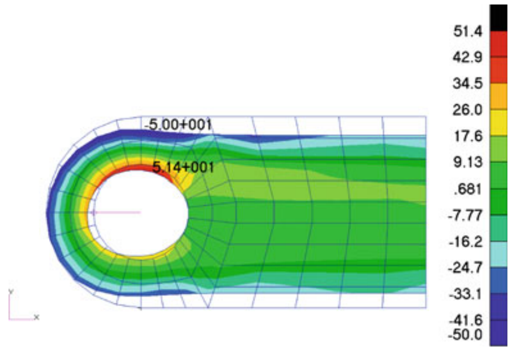

Fig. 15.9 Resulting residual curing stresses in fiber direction [MPa] on deformed plot

simulation methods for real applications. For instance, the path-dependent constitutive (time-independent) pseudo-viscoelastic material model from Svanberg [18] can be applied to predict process induced distortions and stresses. If the spatial temperature distribution is homogeneous within the composite, e.g. in thin parts, a further simplification by Svanberg of evaluating characteristic process

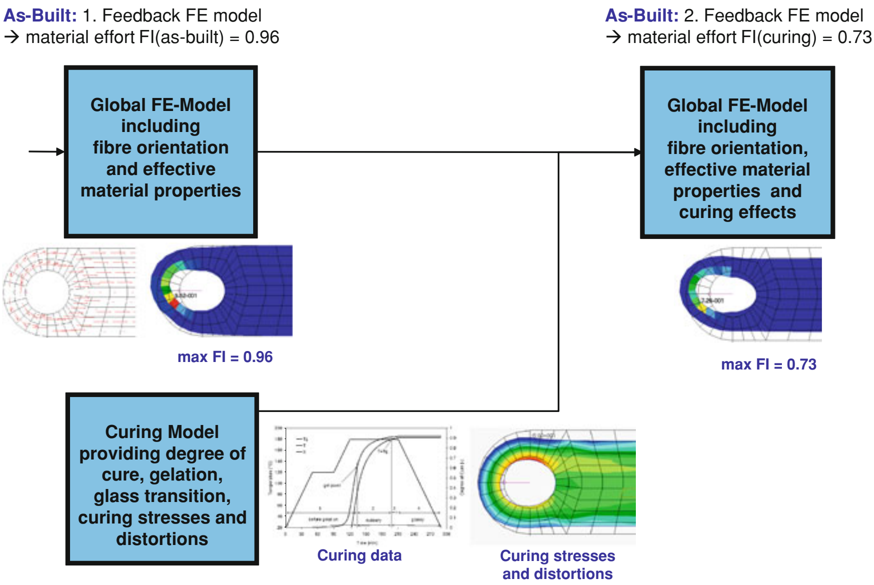

Fig. 15.10 Application of the feedback method to estimate the reduction of load bearing capacity of a manufactured TFP tension strap compared to the first as-built design

steps should be taken into account in order to reduce computation time by achieving the same results. Numerical simulations on simple coupons have already exhibit great accordance between the results from a full transient calculation (applying the path-dependent method) and the results from simplified thermo-elastic calculations (based on characteristic process steps), ref. Wille et al. [20]. For the present TFP strap example, a combination of both simplified simulation methods can be applied in order to predict process induced residual stresses and shape distortions.

Initially, a thermo-chemical simulation is performed in order to predict the degree of cure X and the glass transition temperature Tg at a given process temperature T as a function of time (X = 0 uncured, X = 1 fully cured). From this simulation, the characteristic process steps “gelation” (here X = 0.6), “vitrification” (T = Tg) and “change of curing temperature” (e.g. cool down) can be identified. Based on these results chemical shrinkage effects within the isothermal curing phase can be separated from thermal expansion effects within the heating or cooling phases. As depicted in Fig. 15.8, the curing process is subdivided into four respective steps as listed in Table 15.1.

Hereupon, thermo-elastic calculations are conducted for each step applying the individual material parameters (stiffness, Coefficient of Thermal Expansion (CTE), shrinkage coefficient) of the respective rubbery and glassy states, as described by Svanberg. From these calculations, component stresses and distortions (Ref. Fig. 15.9) can be taken into account as initial conditions for the subsequent structural mechanical analysis and will therefore lead to a change in material effort as well as in the composite failure behavior.

In Fig. 15.10, the "as-built" work flow is extended by the curing simulation step, in order to account for the effect of residual stresses and distortions within a CAE model. By applying the same failure criterion as for the corresponding result plots of the TFP strap example (Tsai-Wu failure criterion), the computed maximum failure index changes from FI(1. as-built) = 0.96 to FI(2. as-built) = 0.73. This reduction of 24% is due to the change of prestressing of the inner fiber tows, mainly arising from resin shrinkage transverse to the fiber direction (radial to the whole), while the length of the tows (in fiber direction, tangential to the whole) are kept nearly constant.

15.4 Outcome of the As-Built Feedback Method

A concurrent engineering, realized by a continuous composite process chain, enables iteration loops for product improvements and higher process efficiency. By means of the developed feedback methods, relevant manufacturing data, e.g. fiber alignments, process induced distortions or residual stresses, can be automatically integrated within the early phase of the future development chain of composite structures. Thus, a less conservative, more robust design is achieved by accounting for different types of constraints and manufacturing uncertainties within the preliminary and detailed design phase.

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