Finite Element Analyses for Selecting and Developing Adhesive Systems

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Abstract

Today, adhesive systems can be precisely tailored to user's demands in a wide spectrum.

From the engineer's point of view this presentation points out the possibilities of using simulation tools with the objective of selecting or developing adhesive systems that fulfill particular requirements best as can.

Examples show how to develop an optimal virtual adhesive system, making the best compromise of properties between a variety of mutually contradictory demands. Using parallel product development routines either on the user's hand (definition of required adhesive properties for special load cases) and the producer's hand (development of the adhesive system so specified) allows for precise optimizations of adhesive systems. Thus, the time consumed by the product development process can be minimized (time to market).

Using stochastic simulations, properties can be found which represent the most powerful factor to yield an effective improvement (Design of Experiments).

Next to this macroscopic point of view methods are described that consider micro-mechanical effects of fillers on thermal and electrical characteristics of the adhesive.

Adhesive Technology in Automotive Engineering

Next to aircraft construction automotive industries are a trend-setter for adhesive applications. With technical enhancements highly-developed production processes and materials come into operation, featuring lightweight construction potential and helping to build automobiles with reduced fuel consumption.

Taking the car body concept of a modern automobile as an example the bandwidth of possible materials and material combinations is shown (Figure 1). These technological achievements require elaborate joining techniques matching with economy, quality and fabrication aspects of established methods and having to fulfill technical demands.

Within the area of conflict of different materials adhesive joining technology shows some main advantages. The plane transmission of forces without borings for mechanical joints (rivets, screws) yields a homogenous distribution of stresses and helps to avoid stress concentrations, allowing for optimized material exploitation. Furthermore, several functions can be fulfilled by the adhesive layer simultaneously (strength durability, sealing, damping, …).

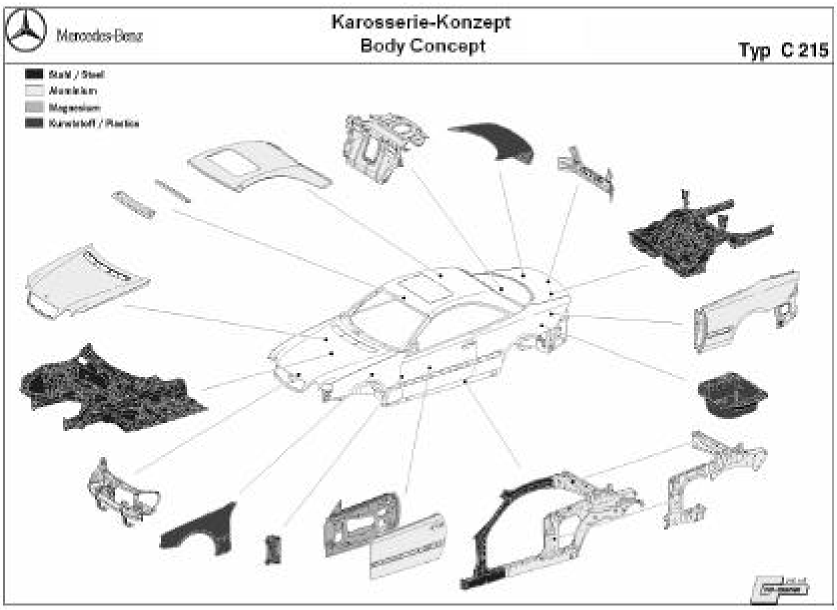

Fig 1: Material Concept of a modern Car Body

Users of adhesive joining technologies stand face to face to a nearly unlimited number of adhesive systems, differing from their chemical base composition and fillers or additives, often showing strongly different properties even within the same chemical family. For automotive concerns Epoxy (EP) and Polyurethane (PUR) systems can be regarded as the most important adhesives.

EP systems are used for structural adhesive joints. Typical features are a layer thickness of some tenths of a millimeter and an elastic modulus ranging from 1500 to 6000 MPa. The higher the elastic modulus, the higher the risk of optically critical marks of the adhesive layer, e. g. in case of thin car body outer blanks. With EP adhesives optimized for crash aspects (adhesion properties, energy absorption capacity) a higher safety for the passengers can be achieved (Figure 2).

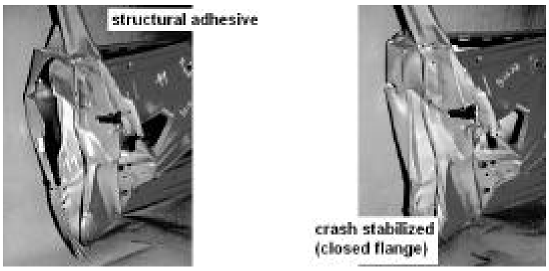

Fig 2: Crash: Improved performance by Adhesive Technology

PUR systems classically are used for adhesively bonded windshields and rear windows (Direct Glazing). A higher torsional stiffness of the car body, thermal and mechanical strain compensation, gap filling capacities (fabrication tolerances) and damping properties (acoustics) play the most important role. The adhesive layer thickness is about 5 mm, the shear modulus ranges from approx. 1 to 5 MPa.

It can be assumed that within a couple of years adhesive technology will be the prominent joining technique in automotive industries.

Thus, for the technical designers the question is: Which adhesive is the best?

Simulation Chain in Automotive Industries

The virtual automobile has become reality in automotive engineering to nearly 100 %. Simulation techniques are used as standard tools of the product development process.

Several software tools are in use, beginning with 3D CAD construction and via software interfaces bridging to FEA, CFD (Computational Fluid Dynamics) and Multi-Body Systems. VR (virtual reality) and user defined tools complete the closed-Loop Simulation Chain (Figure 3).

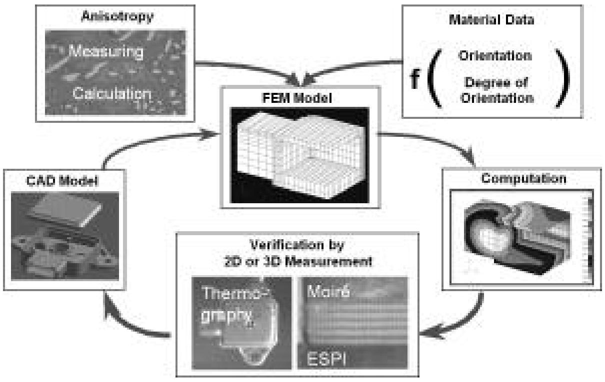

Fig 3: Closed-Loop Simulation Chain

FEM represents a main pillar of the Simulation Chain, offering the possibility of analyzing geometrically complex structures with superposed loading scenarios (static, dynamic, thermal, acoustical, etc.) and efficiently dimensioning the parts. Especially in early design phases, the real prototype is being replaced by the purely virtual prototype. By doing so, cost and time consuming testing can be minimized (iterative improvement) and the verification can be done with quasi optimized parts. For such complex structures analytical calculations are impossible. For crash and airbag simulations special software tools yield results at optimal accuracy-to-computational time ratio.

Today Finite Element Analyses of complete automobiles with 1 million and more degrees of freedom and reasonable computational costs (CPU time) are possible.

FE Analyses of adhesively bonded structures: Application examples and possibilities

With selected examples it is shown which questions of developing and dimensioning components can be effectively answered by today's FEA. It is tried to outline how these techniques may impact the development and quality assurance of adhesives.

Example 1: Sequential vs. parallel Product Development

When it has been decided to adhesively join the components of a construction the technical designers have to define the required geometries. Apart from technical demands also design, economy and production concerns play an important role.

Usually, by considering technical aspects (material, surface properties, production and curing conditions), material costs and given loading conditions a remaining number of potentially suitable adhesives comes into question. This selection is supported by the producers and providers of adhesive systems.

For these variants FE analyses of the loaded configurations are performed, resulting in the proof of fitness for use for some adhesives. Following this pre-optimization, real prototypes are manufactured and tested for verification and technical release purposes. Further procedures for final design and the construction of devices and tools for the production can be planned basing on these results.

In the sum, the FE analyses are done with material data of the adhesives as is (from data sheets, measurement), without using the knowledge of the structural behavior and required or desired properties deriving from FEA results. Then, in some cases the complete construction must be adjusted to the technical performance of the adhesive by changing geometries (further costs for tools) or adherent materials (e. g. high-strength steel). This may lead to conflicts between design, economy and production departments. By sequentially passing through the design process, although making use of simulation techniques great losses in time may occur. Furthermore, chemical modifications of the adhesives can show negative influences on relevant properties and necessitate expensive testing series in order to obtain material data anew.

As an alternative it is possible to establish a parallel design process by integrating the provider in the users' construction process. After the definition of economic, design, material and fabrication conditions the design engineer begins with the FEM-based calculation of the structural behavior under well-defined loads. At this point, purely virtual material properties are assumed for the adhesive layers. Iteratively adjusting the prescribed material data finally results in a set of properties by which the specifications are fulfilled best as can. The most simple scenario would be the definition of a required elastic modulus with static load cases (structural stiffness).

With these information about required material properties of the virtual adhesive at hand, the user contacts the producer or provider. Then, in interdisciplinary collaboration between chemists, physicists and engineers decisions are made

- which of the available adhesives match the demands (databanks, experience), and if none can be found,

- if and how a given adhesive system can be modified, or

- if the development of a new adhesive is necessary.

More complex situations, such as the acoustical optimization of a car body with direct glazing (Figure 4) where next to damping properties also structural stiffness and thermal and mechanical strain compensation capacities have to be considered simultaneously can be effectively analyzed by FEA, too. With respect to mutually contradictory demands the so calculated optimal material properties of the virtual adhesive (elasticity, damping, thermal expansion coefficient) can be exchanged with experts in adhesive development on the producers' side (for acoustical optimization see [KRO02]).

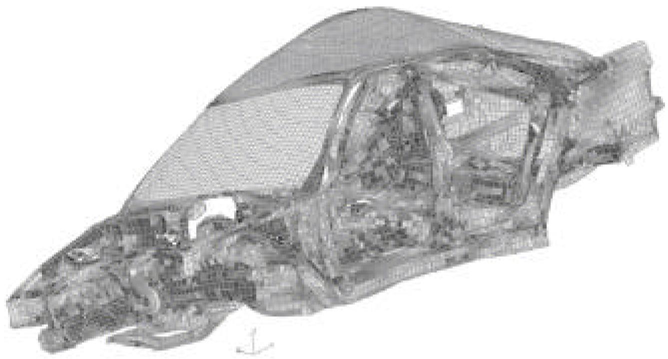

Fig 4: Direct Glazing, FE Simulation of torsional stiffness (see [KRO02])

By using FEA as described above the producers of adhesives can take into account practical demands for adhesive systems in stock already in product development phases or for QA. This target can be reached by establishing FEM capacities, or in collaboration with specialized engineering service providers with FE software, adequate hardware and first of all FEM know how for simulating adhesive joints at hand.

Concerns of interdisciplinary communication (common language, software, data exchange) and non-disclosure agreement and product liability have to be balanced.

Example 2: Stochastic Simulations

In the following paragraphs the methods of stochastic FE simulations are adumbrated and it is tried to show how Design of Experiments concepts can be utilized to develop adhesive systems. For more detailed information about automotive aspects see [REU99] and [REU00], where also suggested literature can be found.

A Finite Element model always is the abstraction of a physical or technical system in a unique and non-ambiguous state. With a qualified degree of abstraction chosen, a suitable mesh and numerical parameters, reliable material data and realistic boundary conditions etc. provided, a reasonable computation of the FE model can be performed within numerical error limits (roundoff).

But, in reality technical systems always show a variance within properties, resulting from manufacturing conditions (e. g. adhesive layer thickness, blank thickness, varying loads), variable material properties and changing environmental conditions (climate). This more or less broad distribution of parameters can significantly influence the system, without having the possibility of considering these aspects in a deterministic model. Unfortunately, the chance that the real system is in its ideal state or in a well-defined state as required for deterministic modeling tends to zero.

Thus, it is the main question how strong the influence of varying parameters or combinations of these is for the response of the loaded system.

A usual method of resolution is to define a worst case scenario and to perform dimensioning simulations for these parameters, trying to absorb uncertainties by safety factors. Due to parameter interaction in complex technical systems it can be impossible to find relevant parameters in such a way that it can be excluded that the structure does not enter an even worse state. On the other hand it can be difficult or impossible to find a set of parameters for which the simulation results are in best accordance with measuring data (e. g. deformations).

Hence, it would be better if the effects of varying parameters could be evaluated by statistics, enabling the designer to define reliable and optimal values. This can be done by cost and time consuming testing series, giving information about strong influencing factors and interaction effects. Because of the great number of empiric analyses required for a reliable evaluation it is more effective to use stochastic simulation methods with the distribution of parameters included in the method. The result also is a statistically reliable knowledge about the structural response at lower cost and time efforts.

The objective of stochastic FE simulations with Design of Experiments concepts is then

- to analyze the effects of varying parameters on the resulting product performance on the basis of a statistical distribution function (random numbers), or

- to find the parameter values for which a given FE model shows best accordance with simulation and measuring data after defining a physically and technical reasonable space of parameters and the reduction of relevant variants (e. g. Taguchi method).

The results of these independent computations again represent a sample of answers which can be analyzed by statistics (reliability). By analyses of correlation the influence of single parameters can be quantified.

Main advantage of using simulation tools is the possibility of parallel computing (e. g. CPU cluster), yielding simulation results quasi simultaneously.

Stochastic simulations are in use in the fields of civil engineering (earth quakes), bio-mechanics and crash simulations [REU99], [REU00]. With increasing hardware performance it will be possible to simulate models with more degrees of freedom or to simulate a given FE model to a more realistic extent, respectively.

For developing adhesive systems or QA concerns the integrated use of stochastic FE methods could help to examine the effects of variable material properties (alternating raw material providers, chemical modifications). Another field can be the improved technical support of the users of adhesive systems by being integrated in the design process with a parallel work flow (see Example 1).

Several software tools for stochastic simulations with automated functions are available (control of FE programs, result reports etc., for example see [REU99], [MAN01]).

Example 3: Micro-structural Material Development

Micro-mechanical approaches have the goal to calculate material characteristics of composites from the behavior of their components. The advantage is that only the properties of the single phases are required. So, measurement efforts can be significantly reduced because changes in volumetric contents or shape and distribution of particles do not require new testing series.

For a long time, analytical formulae are available for the description of the mechanical and thermal behavior of composite materials, especially for fiber reinforced polymers, paper and rubber (tire production) ([COX52], [SCH68], [MAW75], [HAT78], [TAW86]). The capability of these approaches for FEA concerns has been proofed in several projects (e. g. [MOM92], [SCW93], [SCM98]).

For fillers and particles (and combinations) used in adhesives comparable analytical solutions are unknown to the authors, and with respect to the great bandwidth possible with adhesive fillers these approaches may be questionable.

FE methods can help to find a way out of this dilemma. In last years' research projects at ETH Zurich a software tool (Palmyra [MAT02]) has been developed, based on the same fundamental idea as described above, allowing for calculating a lot of physical properties of composite materials beginning with a small basic cell.

In the following paragraphs these aspects are described for adhesive development concerns by taking an actual technical project as an example [IFF03].

Today, modern materials technologies enable the creation of materials with characteristics tailored to specific demands in a great number of fields of application. Typical examples are filled and fiber reinforced polymers, Metal-Matrix- and Ceramic-Metal-Compounds (MMC, CMC).

The properties of such compounds do not only depend on the behavior of the single components, but also on the volumetric content, shape and distribution of additional phases. Generally, to determine the compounds' properties numerous samples are produced and tested. Based on experience, encouraging material prototypes are manufactured for testing series (Trial & Error).

It is more effective to carry out computer simulations for systematic optimizations of the required material, even before any real prototype has to be produced. This can be done by using the software "Palmyra" which is based on FEM and allows for creating statistically independent variants (Monte-Carlo method). By software interfaces the optimized material data can directly be assigned to FE programs.

The work flow of such a material simulation starts with the definition of the shape, size and orientation of fillers or fibers in the matrix material, representing the basic cell for the computation, followed by the creation of statistically independent morphology variants. For the components material data is defined. Modeling ends with automatically creating FE meshes of the basic cells.

Next step is the calculation of the properties of these heterogeneous cells. It is possible to compute the following characteristics:

- elasticity,
- stability of foams,
- thermal conductivity,
- electrical conductivity of poly-cristalline metallic alloys,
- thermal expansion coefficients of partially cristalline polymers,
- refraction index of Nano-Composites,
- gas separation of composite membranes.

Calculations are completed by visualizing the results (stress fields, current or heat flow, etc.), allowing for virtual evaluation of the material behavior. Finally, from a quasi endless number of possible variants the best material configuration can be filtered out.

For adhesive development concerns, fillers and particles can be examined and an optimal configuration (size of particles, distribution, shape, etc.) can be calculated for specified demands. This could help in optimizing electrical and thermal properties of adhesives used in induction curing of adhesively bonded front hoods made of polymeric materials (Figure 5). In such a process the heat is generated within the adhesive filled with electroconductive particles (metal, nano-ferrites), resulting in minimized distortion of the part [IFF03].

For QA stochastic FE simulations could help to analyze variable material properties on the microscopic scale, as described in Example 2.

Another advantage is the high degree of details possible with small micro-cells to be analyzed (CPU time, variants).

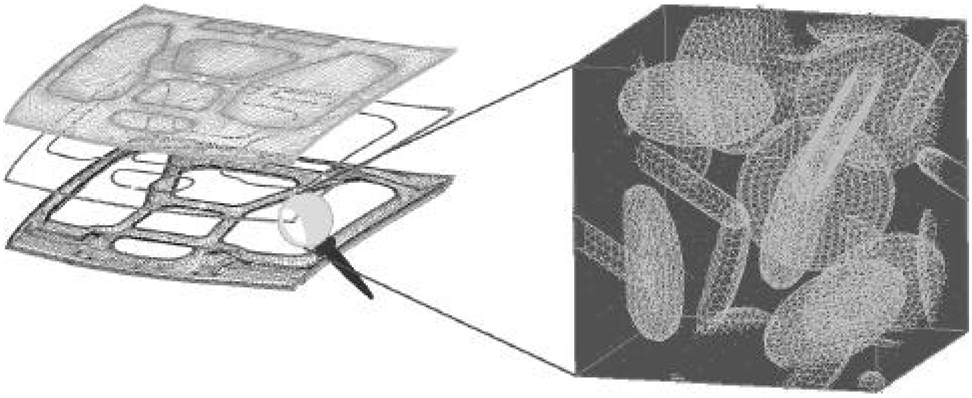

Fig 5: Material Optimization with Micro-FE-Cell

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