

Finite Element Analyses of structural glazing elements in civil engineering and adhesively bonded windshields in automotive engineering – a comparison

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Abstract

Due to numerous technologic and economic advantages and constant advancement adhesive and sealing technologies are used in increasing extent both in mechanical engineering and civil engineering. Especially structural adhesive joints with multi functionality and high potential for the future are targeted.

In this presentation the possibilities of Finite Element Analyses are discussed from the mechanical engineer's point of view, taking as an example structural glazing facades in civil engineering and adhesively bonded windshields (direct glazing) in automotive industries.

In civil engineering structural glazing has been a success in Europe for a couple of years. Due to their high durability and a wide range of adhesive properties only silicones are approved, which usually are used as classical sealant materials. Dimensioning is done by analytical formulae and safety factors based on experience of many years. Standardized test methods and test items similar to real components help to characterize mechanical properties of the adhesive systems and their durability under climatic influences [1]. The facade elements are subject to construction inspections.

In automotive industries, direct glazing is a typical application of adhesive technology. Windshields and rear windows are adhesively bonded to the car body. Apart from an increased torsional stiffness of the structure combined sealing functions and acoustic damping effects are further advantages. For experimental characterization of adhesive and compound properties standardized methods and part modules are used likewise (e. g. [2]). Today, FEA is used as standard tool for technical design layout (digital automobile). Simulating various load cases leads to constructive upgrades and helps to develop direct glazing concepts with features tailored to technical demands.

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In general, structural adhesive joints in automotive applications are made of epoxy systems with a high shear modulus. The adhesive layer thickness is about some tenths of a millimetre. Due to low flexibility of the bond, these adhesives cannot be used for direct glazing because of critical stress concentrations within the glass panels and the risk of fracture in case of higher distortion (parking one tire up the curbstone). This problem can be resolved by a higher flexibility of the joint (lower shear modulus of the adhesive) and thicker adhesive layers (allows for relative motion through the joint). To achieve this, PUR adhesives (shear modulus approx. 3 MPa) with layer thickness of about 5 mm are used. Thus, by customising the flexibility of the joint the quasi rigid glass panel contributes to global stiffness of the car body (semi-structural adhesive joint). These aspects also play an important role with structural sealant glazing (official denotation [1]) with regard to an even lower shear modulus of silicones and a layer thickness of approx. 7 mm.

The following paragraphs give an overview about relevant aspects for both mentioned applications and methods for FE simulations are described.

Structural Glazing

Main advantages:

- new design concepts
- improved thermal insulation
- integration of functions sealing/carrying loads/isolating
- modular design
- acoustics (noise insulation)
- self-cleaning property (lower maintenance costs for facades)

Requirements and civil engineering aspects:

- construction supervision and specification tests
- external quality control
- dimensioning by analytical and empiric formulae
- durability (humidity, UV radiation, temperature changes, etc.)
- adhesion to different substrates, possibly single case studies required
- mechanical supports absorb static loads (self-weight of panes) [1]
- high safety concerns
- Germany: retaining devices from installation heights > 8 m [6]
- demand in case of failure: purely cohesive break-down of adhesive [6]

Adhesives and assembly materials:

Because of their high durability against climatic influences and a wide spectrum of adhesive properties with different surfaces only silicones are used as adhesives (single-phase moisture setting or two-phase systems). For this decision, long-time experience with these sealant materials and their robustness plays an important role.

The adhesive layer thickness is about 7 mm [3], being calculated analytically depending on the length of the short element's edge and the maximum wind load expected (supported systems).

Glass as hydrophilic material generally shows problematic adhesive characteristics. In civil engineering, panes are often coated to improve thermal insulation or show anti-reflecting features. In some cases, these coatings must be removed from the joint surface. To avoid interface migration of moisture, surface pretreatment of the panes is required.

Substructures of structural glazing elements consist of anodized or powder-coated profiles made of aluminum alloys or stainless steel. With powder-coated surfaces bonding agents may be necessary (primer).

Further parts not being part of the adhesive chain directly, such as spacers and sealants, are made of a variety of polymeric materials. Compatibility to silicone adhesives must be verified from case to case.

The proof of suitability of silicones as structural glazing adhesives possibly requires time-consuming and costly experimental tests for particular technical demands, according to regular specifications.

FEM aspects with Structural Glazing:

As mentioned above, analytical formulae and safety factors are used for dimensioning structural glazing units. In doing so, stress states can only be calculated in homogeneous distribution.

FEM can help to analyse superposed load cases and deduce ideas for constructive and materials improvements. As a main advantage the possibility of taking three dimensional stress and strain states into account leads to optimizations in order to avoid critically stressed regions. For insulating glass units, one important load case are pressure gradients between the atmosphere and the interspace between the panes (enclosed atmosphere).

In general, most of the load cases relevant for civil engineering can be analysed by FEM. These are static, thermal, dynamic and acoustic simulations. As an example, the simulation of inhomogeneous temperature distributions can be a valuable source for detecting maximum stresses in local regions (simplified model, no thermal conduction, without enclosed atmosphere):

Maximum principal stress after inhomogeneous heating, qualitative, exaggerated deformations

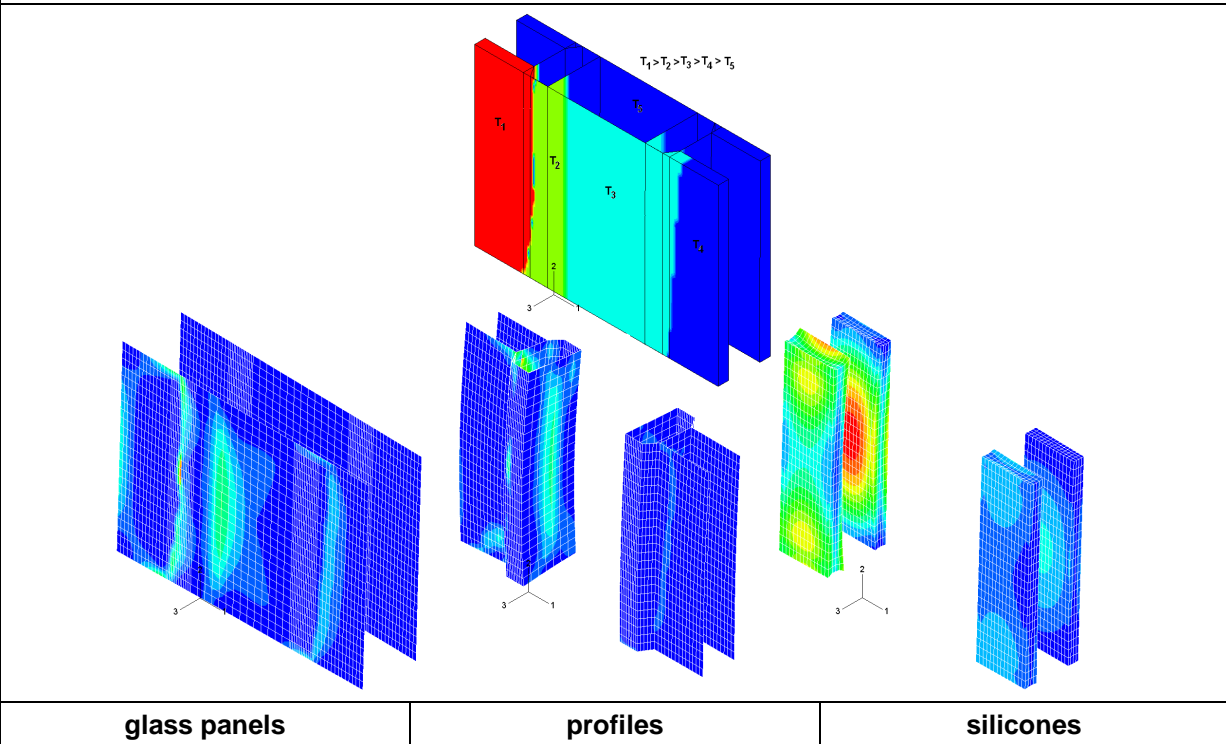


Figure 1: approval body SSG element, simulation of inhomogeneous temperature distribution (see [6])

If plausible material data can be supplied (measuring expenditure) time and temperature dependent effects (e. g. creep, hyper- and visco-elasticity) within the silicones can be analysed with prevalent general purpose FE program systems. For comparing purposes even linear-elastic material definitions can yield valuation concepts for the structural behavior (for small strains). Aging effects can only be investigated by giving material definitions directly from measuring data (e. g. stress-strain-curves).

Today, extremely thin films and adhesive effects (interface) cannot be reproduced by FEM means. For simulations materials can only be characterized by their core properties.

Visionary speaking, beginning with well-defined load scenarios a virtual adhesive could be defined by means of FEM. The required material properties could be passed on to producers and manufacturers with the objective of developing or chemically modifying adhesive systems matching these demands.

Direct Glazing

Main advantages:

- higher stiffness of the car body (especially torsional stiffness):

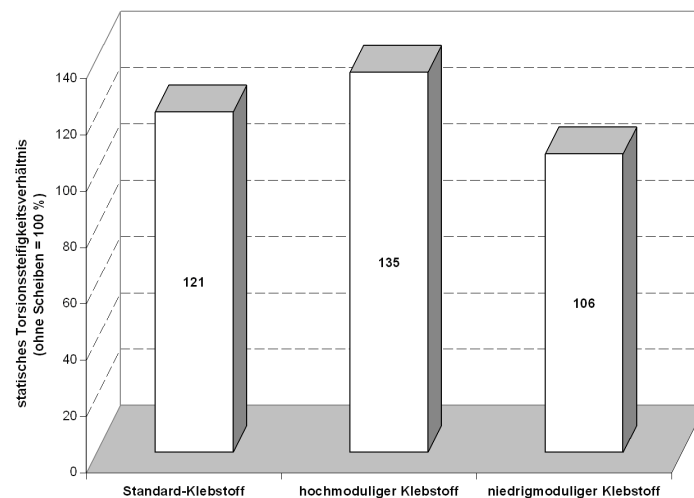


Figure 2: higher torsional stiffness of car body by adhesively bonded windshields (see [2])

- mass reduction potential (more slender A-, B- and C-Pillars)
- acoustics (vibration damping)
- integration of functions sealing/load bearing capacity/isolating
- design

Requirements and technical aspects:

- compensation of differential thermal expansion characteristics (flexibility, adhesive layer thickness)
- sufficient flexibility of the structure under mechanical distortion (see above: parking one tire up the curbstone, risk of glass panel fracture)
- quick handling stability (no mechanical fixation) [4]
- sufficient strength in short time (driving test on bad road)
- durability (humidity, UV radiation, heat)
- avoidance of pretreatment of adherent surfaces (bonding directly to coated surfaces)
- electrical isolation (antenna integrated into rear window)
- climate-controlled production (adhesives setting with humidity)
- repair at garages (replacement of fractured glass panels within 3 to 4 h [5])

- demand in case of failure: purely cohesive break-down of adhesive [4]

Adhesives and assembly materials:

Polyurethane based adhesives are used with a typical adhesive layer thickness of about 5 mm [4]. In comparison to standard PUR adhesives these systems show higher shear moduli (2,5 up to 3,5 MPa vs. 1 MPa) and can be optimized to specific damping properties. In addition, these systems must withstand environmental influences. Ceramic coatings on glass panels absorb UV radiation.

PUR adhesives for direct glazing can be moisture setting single-phase or cure-accelerated systems.

The curing process of moisture setting single-phase PUR depends on environmental conditions. A skin is formed at the outer surface constricting the curing progress within the volume. Due to insufficient handling stability mechanical fixation of the glass panels is often required.

Accelerated curing can be achieved on the one hand by adding aqueous second phases which improve moisture dependent cross linking processes throughout the volume. On the other hand hot melt adhesives can be added serving as tacky constituent when heated to approx. 80 °C. After joining the glass panel, this component cools down and becomes rubber-like with sufficient handling stability. Mechanical fixations are no longer necessary in this case.

Glass and steel (coated) are the most important adherent materials. Car body structures made of aluminum alloys today still are rather exceptional.

FEM aspects with Direct Glazing:

In automotive industries FEM is used as integral part of a closed loop simulation process chain to develop an optimized virtual prototype (reduced time to market).

Structural simulations such as the analysis of the torsional stiffness of a car body yield information relevant for final design:

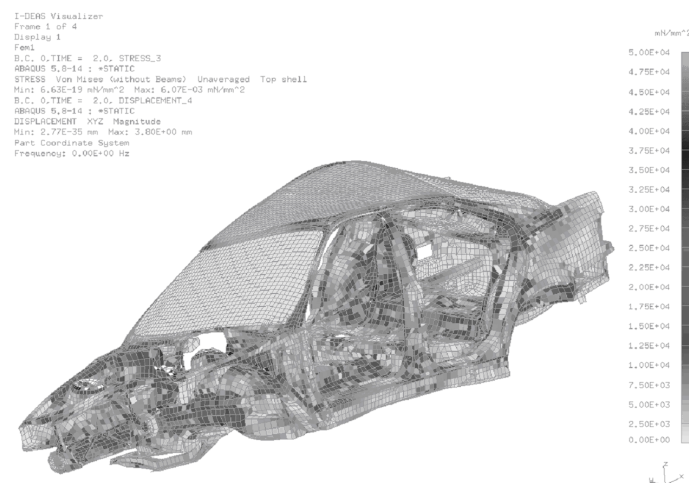


Figure 3: FE calculation of static torsion of car body with direct glazing [2]

Complex geometries are analysed under superposed loading conditions to optimize the adhesive layer thickness and width or to check gap dimensions between adjacent parts. In the near future simulations of complete automobiles with up to 1 million finite elements are targeted (hardware capacity).

As above, with realistic material data at hand non-linear or time and temperature dependent effects can be taken into account.

Following [2], for acoustic optimizations of direct glazing car bodies (critical region: rear window) adhesives with low modulus and high damping capacities are required (definition of adhesive properties by simulation). Standard PUR systems with these characteristics possibly fail to fulfill structural demands. In the sum, by defining required material properties by FEM modifications of adhesives or even completely new approaches (two phase direct glazing adhesive system) can be defined.

Possibilities of FEM for Structural Glazing in comparison to Direct Glazing:

Regarding the aspects outlined above, the following table gives a summary of the possibilities of using FEM as design tool for both applications (without claiming for completeness):

	Structural Glazing	Direct Glazing
FE Modeling	2D CAD (e.g. [7]), Shells and Solids	3D CAD, Shells and Solids, simulation process chain
adherent materials	glass, steel, aluminum	
adhesives	Silicones (low stiffness, high tensibility, high elongation at break)	Polyurethanes (moderately higher stiffness, quasi incompressible, high tensibility)
test methods and verification	standardized specimens (adhesion, cohesion), approval body, modules, prototype, field trial (long term), external supervision	national and international standards, internal standards (e. g. salt spray test), modules, prototype (driving conditions), worst case scenario (field trial „Sahara“), Technical Inspection Agency
FE analyses	static (self weight, stress concentrations, canted panels) thermal (climatic changes, inhomogeneous heating, thermal conduction) coupled thermal-mechanical dynamic (wind pressure and suction, earthquake) non-linear material time-dependent (creep, visco-elasticity) modal analyses insulating glass: simulation of pressure gradients design optimization FE-simulation of residual stresses and shrinkage effects [8] QA: effects of variation of material properties stochastic FE methods	static (deadweight bearing capacity, torsional stiffness) thermal (e. g. solar radiation) dynamic (wind, vibrations under driving conditions) non-linear material time-dependent (hardening-effects of blanks, creep, visco-elasticity) modal analyses simulation of airbag inflation (impact on windshield) design optimization FE-simulation of residual stresses and shrinkage effects [8] QA: effects of variation of material properties stochastic FE methods

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