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**Development of consistent calculation models for cold-bent glass panes used in single-glazed, laminated and insulating glazing, point or linearly supported (BEKAGLA)
IGF-Nr.: 22697 N**

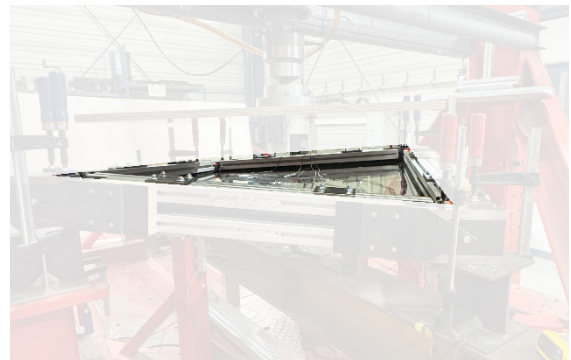
Summary of the research project AiF No.: 22697 N

The load-bearing, deformation and strength of permanently cold-bent glazing - ranging from basic single-pane glass to laminated and insulating glass - presents the structural engineer with a wide range of challenges. The aim of the research project was to develop a comprehensive design concept that takes into account the stresses induced during geometrically non-linear forming and the stresses caused by external loads. To this end, new test rigs were developed, extensive tests on components and small parts were carried out, and experimentally validated computational models were established. The findings were subsequently incorporated into an informative annex to EN 19100-2. To begin with, two complementary test methods were developed: a modified four-edge bending test produces a largely uniform edge stress distribution, even with high breaking loads in thermally toughened glass. A four-point torsion test simulates the combined membrane and bending stress conditions that occur in anticlastically cold-bent panes. The 80 reference tests enabled a statistical description of the edge strength to be established.

Furthermore, the influence of cold bending on load transfer, stress redistribution and the stability of single-pane glass sheets was investigated. Different aspect ratios and thicknesses were supported at the corners or along the edges, and subjected to surface and point loads at varying degrees of cold bending. The test set-ups yielded reproducible force, deformation and strain curves. As cold bending increased, the dominant tensile stresses shifted from the centre of the pane to the outer regions. Linear support increased the system stiffness and significantly stabilised the deformation pattern. The tests served to validate geometrically non-linear FE models. As a closed-form analytical solution to the von Kármán equations could not be obtained in a sufficiently manageable form, the analytical findings were incorporated into a physically informed neural network. This network models the investigated geometries with high accuracy and, once trained, enables complete field solutions to be obtained within milliseconds. This provides a powerful tool for parametric studies and design tasks. Furthermore, the time- and temperature-de-

pendent shear coupling of cold-bent laminated glass panes was investigated. In this study, the interlayer, temperature, degree of cold bending and type of load were varied. The combined effect of increased system stiffness resulting from higher shear bonding was demonstrated for both cold bending and the subsequent loading. FEM models were able to take into account creep, relaxation, temperature and the actual temporal loading history simultaneously. In addition, the findings were applied to double-glazed insulating glass units. Different spacer thicknesses and designs were investigated. The measurements demonstrate how cold bending and resulting cavity geometry alter pressure coupling, load distribution and the location of the dominant stresses. In addition, edge-sealed specimens made from five material combinations were tested under tension, compression and shear. The developed H-specimen enabled the reproducible determination of spring characteristics. The validated FE model couples the panes via a fluid cavity and discrete edge springs derived from small-scale tests. Stresses and force-deflection relationships are represented very well, and the computational effort is significantly reduced compared with detailed modelling. Finally, the results were compiled in an in-

formative annex to EN 19100-2. The draft contains product-specific rules for the viscoelastic shear coupling of laminated glass, as well as for the air gap, spacers, sealants and gas tightness of insulating glass. It addresses load-bearing capacity, serviceability, ultimate limit state, mountings, substructures and replacement conditions. For complex geometries, geometrically non-linear finite element analyses, including imperfection and convergence studies, are required. The project has established a seamless link between experimentation, numerical modelling and standardisation. The key mechanisms involved in cold bending have been quantified for the most important glass building products and translated into specific calculation requirements.



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