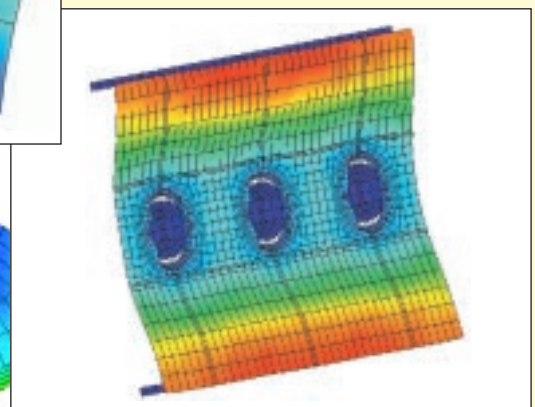
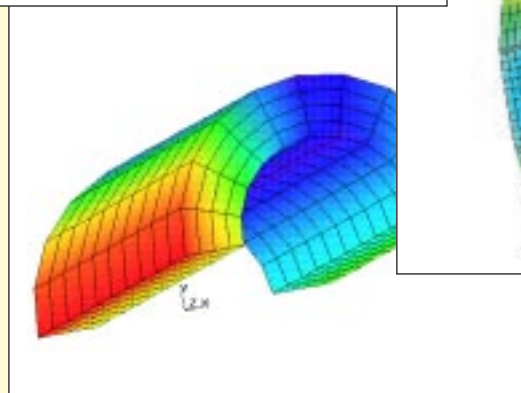
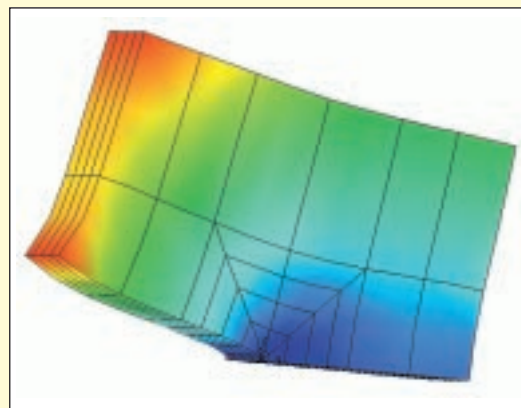




# **B2000, a Modular Finite Element Analysis System**

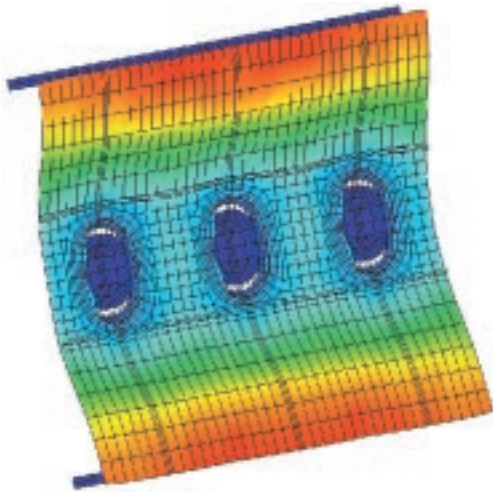
Development and Applications



# The Modular Finite Element Analysis System B2000: Development and Applications

Advances in computational mechanics are often developed on a finite element basis. To be able to build new developments, a modular finite element code is necessary as a testbed. The National Aerospace Laboratory NLR uses the modular finite element code B2000 for this purpose, among other things. This code consists of a number of 'processors' that communicate via a central data base, called MEMCOM.

NLR acquired B2000 from the originator SMR Engineering and Development in 1986, and has used it since for research and development in fields including post-buckling, vibro-acoustics, optimisation, damping and thermal analysis. Currently three universities of technology and two of NLR's sister aeronautical institutes use B2000 as a testbed, too. NLR is pursuing a co-ordinating role in the development of B2000 by initiating collaboration projects between B2000 partners and offering support.



Deformation of window area in an ultra high capacity aircraft due to cabin pressure

## A short introduction to B2000

B2000 has emerged from the need for a modular, hardware-independent, user-customized numerical analysis system which corresponds to modern software standards. Although primarily designed for finite element computations, B2000 also encompasses other numerical methods. B2000 is written in Fortran 77 and ANSI C. Owing to its modular design, however, B2000 is not limited to Fortran and ANSI C environments.

### The main features

#### Modular design

B2000 consists of a series of physically independent program modules (processors), each of which performs a logically defined task. Data transfer between modules

always occurs through the data manager. Processors may be executed separately or in a cluster. The modular design of B2000 enables the user to select the necessary processors for solving a specific problem. New independent processors may be added to B2000. This feature is particularly suited for users wishing to develop their own methods.

#### Data base management and data structure

The most important feature of a modular system is a well-defined and consistent data definition. This implies:

- self-descriptive and transparent data throughout all modules;
- data transfer between modules exclusively via the global data base;
- a client-server based network manager which maintains the communication between data base files through a multi-machine network.

The MEMCOM data management package of B2000 provides the necessary tools.

#### Solution techniques

B2000 is designed to deal with a wide range of problems. Substructuring, partial element assembling and penalty functions are integral parts of B2000. The solvers can handle non-positive, complex and asymmetric problems. There is no *a priori* limitation to the number of degrees of freedom. Eigenvalue solvers based on the subspace iteration method are available for the solution of the generalised complex eigenvalue problem. Standard modules for the solution of non-linear problems (Riks' path following method, modified Newton method) are provided.

#### Element techniques

B2000 contains a standard library of elements for solving elasticity, acoustic and Laplace-type problems.

Users may easily add their own elements to B2000. There are no limitations to the number of nodes per element, or to the number of degrees of freedom per node.

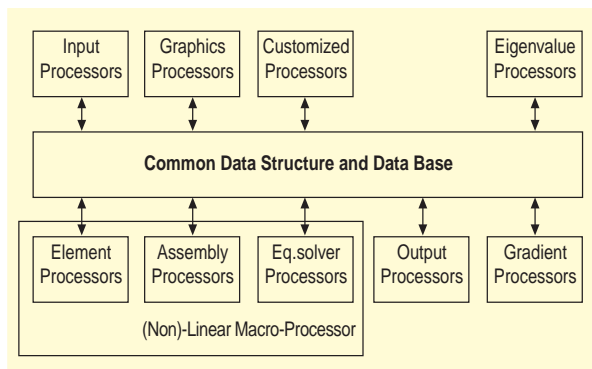
### Input and output

Input to B2000 may be directed to the Input Processor. Alternatively, the input data may be set up directly in the global data base format. All B2000 output data may be accessed through the global data base or by the B2BASPL graphics processor. The data may of course be translated to fit any other pre- and post-processing system.

The modular design of B2000 and its integration in the MEMCOM data base management system are easily adaptable to distributed processing environments. The entire B2000 documentation, including the data base description and the user manuals, may be accessed on-line.

### Architecture of B2000

As mentioned above, B2000 consists of independent processors which are connected to a common data base. All information necessary for a run (including input and commands to the individual processors) is contained in the common data base.



*The basic structure of B2000*

Processors consist of kernels which call the subroutines needed for performing the logical functions required by the processors. The kernels are FORTRAN or C subroutines which must be called either by a main program or a main subroutine. Main programs for all processors are included in B2000. Processors may also be clustered by linking them into a common executable code.

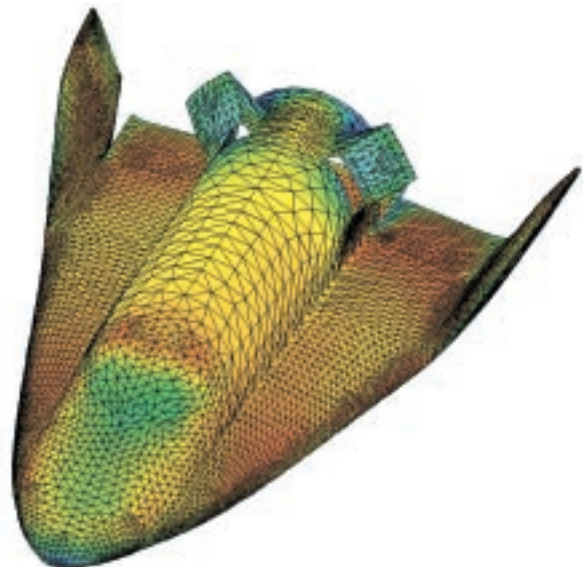
Special emphasis has been put on co-ordinate transformations. Facilities are provided for transformations from global co-ordinates to substructure-local co-ordinates and from node-local (surface) co-ordinates to global co-ordinates.

For a standard linear stress analysis the B2000 processors perform the following tasks:

- The Input Processor B2IP translates an input data file with connectivities, material properties, node numbering etc. into the form required by the B2000 data definition.
- The Element Processor B2EP computes element matrices.
- The Assembler Processors B2AEM and B2ABV assemble the global stiffness matrix and force vector from the element matrices and vectors.
- The Equation Solver B2ES calculates the deformations.
- The Gradient Processor B2GRAD evaluates the stresses element-wise.
- The Reaction Processor B2RCF computes the reaction forces for all nodes of a structure, thus providing a method for checking the equilibrium (linear analysis).

The Macro-Processor B2LIN includes all processors mentioned before, enabling the whole linear analysis to be carried out at once.

### Post-processing and interfacing



*The distribution of the local Mach number over a spacecraft body (landing configuration)*

The post processor B2BASPL allows the results (deformation, stresses) to be visualized by means of various techniques, including contour plots and diagram plots. The visualization program is optimised for high-performance graphics workstations, such as Silicon Graphics systems.

With the processor B2NAS, a NASTRAN bulk data deck can be transformed to a B2000 input deck. Transfer the other way around is possible too. In the latter case a NASTRAN bulk data deck is generated

from the B2000 data base file. With the pre- and post-processing program PATRAN, NASTRAN bulk data decks can be generated, which means that B2000 has an interface with all analysis programs that have an interface with PATRAN.

## Validation

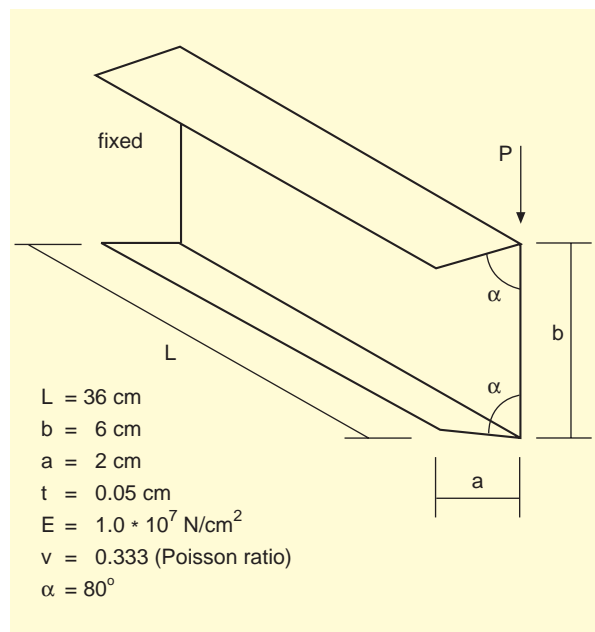
B2000 is a testbed and therefore always under development. New features are added, bugs are fixed, parts are reprogrammed to increase the computational speed or to take full advantage of new computer features such as parallel processing.

The code developments are carried out by several institutes in Europe. Every now and then the different codes are merged and a new version is released. To check whether a new version is still capable of solving problems which have been solved in the past, a special test processor (B2TEST) is available. It contains a series of documented problems which can be run automatically. The users can add new test problems for their specific developments in an easy way.

## Research topics

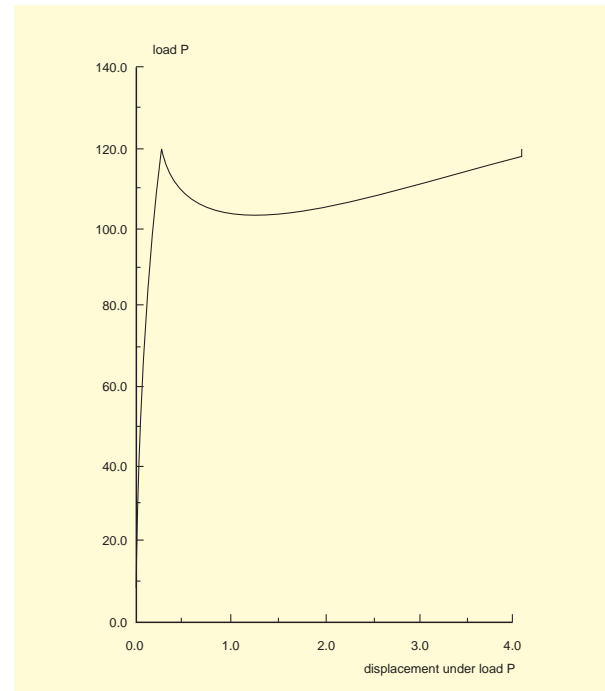
### Buckling and post-buckling

B2000 is used as a testbed for the development of methods for non-linear analysis of buckling and post-buckling of thin-walled stiffened shell structures made of metal or composite materials.



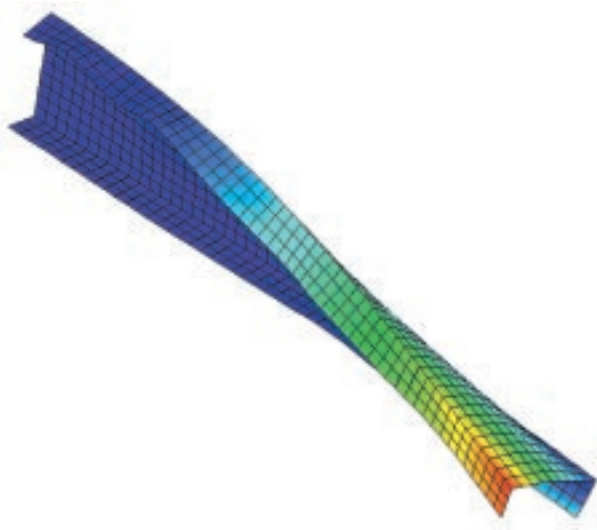
*Schematic view of a U-beam subjected to a post-buckling analysis. The flanges are not perpendicular to the base and the structure has been modelled with the SIMO-type shell element*

Currently linear buckling analyses and post-buckling analyses can be performed with non-linear shell and volume elements. For post-buckling analyses, tools for the Modified Newton method and the Path Following method are available. These tools have been used for the design of composite shear webs. When applying the calculated strains to Tsai Hill's failure criterion, the most critical locations could be detected, and were found to be identical to the locations where failure was initiated during tests.



*Load-Displacement relation of the U-beam tip, near the load point*

In the framework of the B2000 research on buckling and post-buckling behaviour of shell structures at the Delft University of Technology, a family of non-linear shell elements capable of handling large strains, large displacements and large (finite) rotations is developed on the basis of the SIMO-type shell theory. In this theory a single director (first order shear theory) assumption is used to describe the deformation of the shell. Hence, a point of the shell is described by a midsurface position vector plus its distance from the midsurface measured along the so called director. Using a constraint equation that makes the drill rotation equal to the rotation of the midsurface about its 'normal', stiffness is also computed for the drilling freedom. In this way stiffness is computed for all the six nodal freedoms, which is particularly useful for modelling non-smooth shell intersections as presented in the example of the U-beam. However, it is not allowed to load a drilling freedom directly by a drilling moment, since this type of loading is excluded by the shell theory that is used.



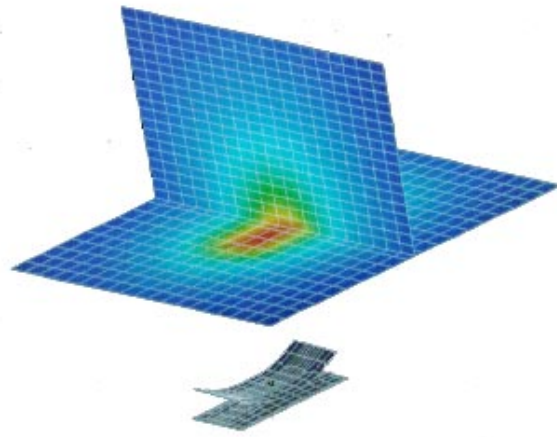
*Deformation plot of post-buckled U-beam*

Three shell elements have been developed with 4, 8 and 9 nodes. They use isoparametric interpolations for the displacements and the geometry. To prevent in-plane locking problems, a combination of nonconforming displacements and incompatible modes is used. The so-called ‘tying-point’ interpolation of Bathe is used to prevent out-of-plane shear locking. This tying point interpolation is based on the computation of the out-of-plane shear strain at a number of (tying) points in the element and then using the resulting values to interpolate this strain in the interior of the element. The locations of the tying points are chosen such that Kirchhoff-type pure out-of-plane bending can be captured exactly, without introducing out-of-plane shear locking even for very thin shells.

### Acoustics

In several research programmes, B2000 is used as a testbed for the development and evaluation of coupled structural-acoustic analysis methods. To this end a number of new elements and solvers have been developed. For the modelling of fluids, special acoustic elements (both linear and quadratic ones) have been developed. The fluid is assumed to be compressible, inviscid and at rest (zero mean velocity). For fluids without energy dissipation two elements are available. For the modelling of two-phase materials (e.g. glass wool) a limp acoustic element (neglecting the stiffness of the fibre matrix) has been implemented, with which the acoustic behaviour and also the dissipation capabilities of the material can be modelled. Currently a two-phase Biot element (in which the stiffness of the fibre matrix is taken into account, too) is implemented. To model the energy dissipation on the surfaces of acoustic domains, impedance elements have been implemented. Special elements are available to couple the structure with all of the above-mentioned acoustic

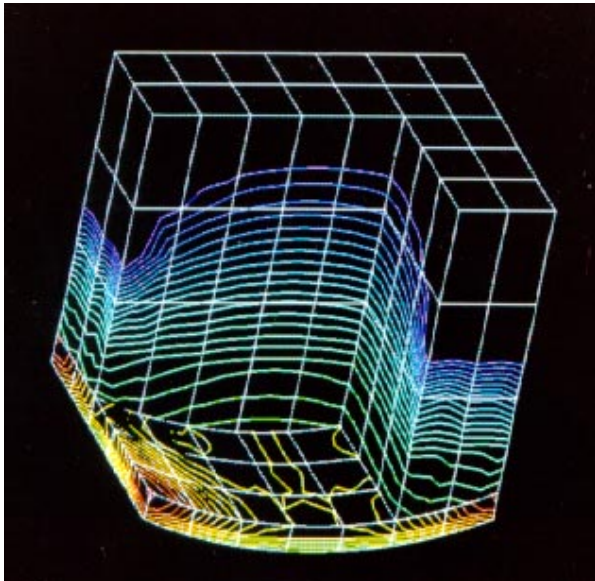
elements. Infinite domains can be modelled with special elements (infinite wave envelope elements), but also boundary elements (both direct and indirect methods) can be used. The coupled structural-acoustic problem can be solved with solvers developed for the generalised eigenvalue problem with complex symmetric as well as complex non-symmetric matrices. In the latter case both left and right eigenvectors are calculated.



*Sound pressure distribution due to vibrating double wall structure in two perpendicular planes in receiving room above double wall*

It is also possible to obtain a solution for the equations of motion in the frequency domain with the so-called frequency response processor in which the system matrices can be complex, symmetric or non-symmetric. So, all kinds of matrices are allowed. Different solution methods, direct and a number of modal methods, are available. Damping is introduced by means of Rayleigh or modal damping, or through the imaginary parts of the matrices. Further it is possible to calculate the sound intensity at points in the fluid domain. These points do not have to be located at nodes, but may be positioned anywhere in the fluid domain. Other acoustic quantities can also be obtained, such as: incident power, transmitted power, transmission loss, reactivity, etc.

In order to describe the propagation of sound waves in visco-thermal media, at the University of Twente a special model was developed. The model includes the effects of inertia, viscosity, compressibility and thermal conductivity. Because the model is written in terms of dimensionless parameters, the transition between the different flow regimes can be easily demonstrated. Based on this model, a special acoustic finite element was implemented in B2000. The acoustic element is

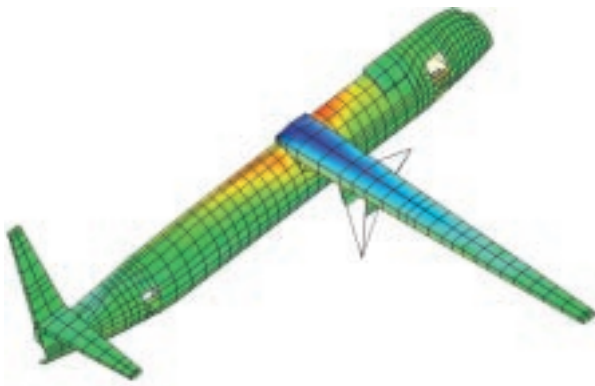


*Acoustic pressure distribution in a cavity between two flexible curved panels and in the receiving box above the double wall structure*

capable of describing the pressure distribution in a narrow gap for complex geometries. The element can be coupled with structural elements, enabling fully coupled structural-acoustic calculations to be carried out.

### Optimisation

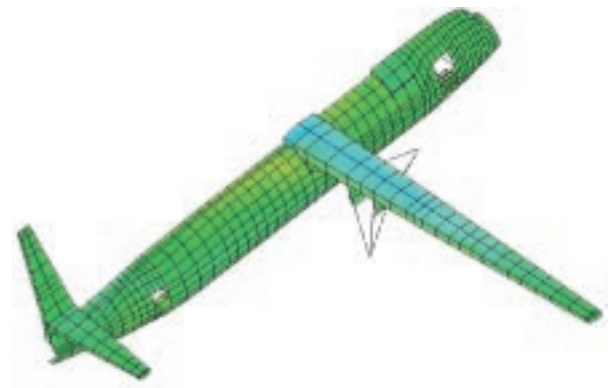
B2000 has been extended with a module to perform sensitivity and optimisation analyses (B2OPT). This module is capable of optimising a structure subjected to constraints such as displacements, strains, stresses, reaction forces, buckling loads and modes, eigenfrequencies, eigenmodes, mass and gauge limits.



*Initial stress distribution in Fokker 50*

The design variables are any (linear) user-defined combinations of: node co-ordinates, node masses, node forces, element (ply) thickness, element cross sectional properties, element (ply) material angles, element density, element loading, material properties and constraint allowables themselves. The objective is one of the constraints specified by the user.

Currently the capabilities are extended to incorporate constraint types such as acoustic frequency and transmission loss and (un)steady aero-elastics (flutter, static divergence). The optimisation process itself is based on the approximate model concept, while in this implementation second order approximations are used. The first order sensitivities are calculated using a semi-analytic finite difference scheme and the second order sensitivities are derived with update methods (BGFS). The convergence of the optimisation process is accelerated using advanced screening, normalisation and scaling techniques. B2OPT has been used to design the structural layout of aircraft in several national and European projects. As an example the re-design of a Fokker 50 is shown.

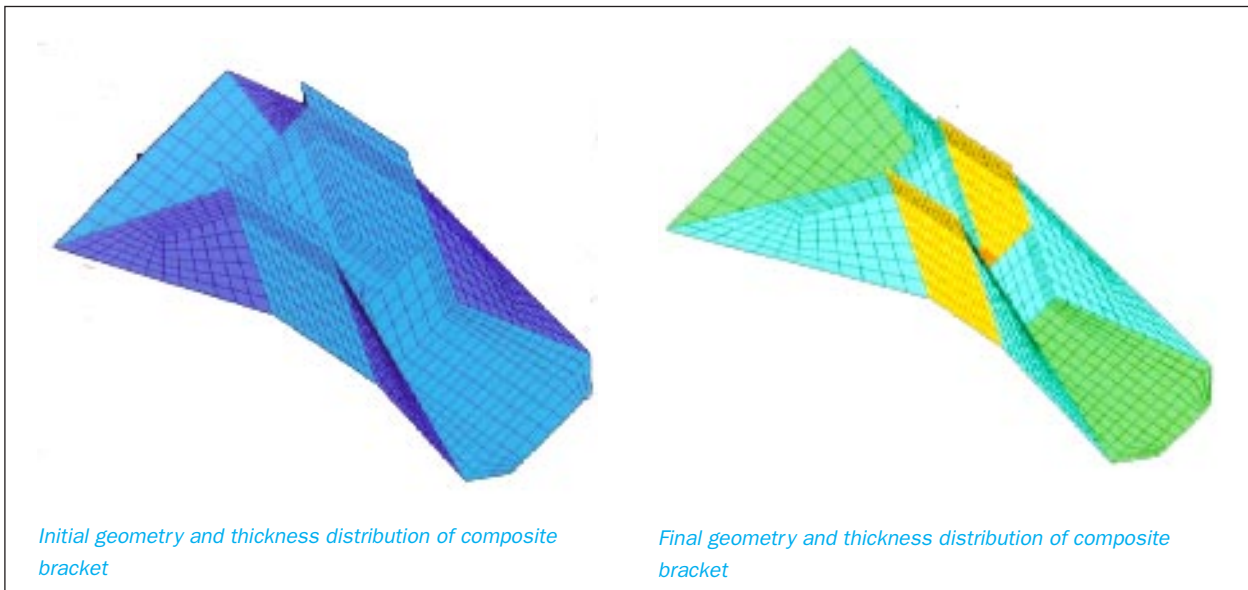


*Stress distribution in Fokker 50 after optimization with the thickness of the fuselage and the wing as design parameters*

Besides for global aircraft design, B2OPT is used for the structural detail design of parts too. As an example of this detail design a composite bracket for launchers is shown. The optimization resulted in a different geometry compared to that of the metal bracket configuration, and laminates with optimized ply thicknesses.

### Damping models

For the analysis of the dynamic behaviour of a structure, damping plays an important role. A common method is to use a modal base for the response analysis and to add modal damping, which value is obtained experimentally or chosen (based on experience),

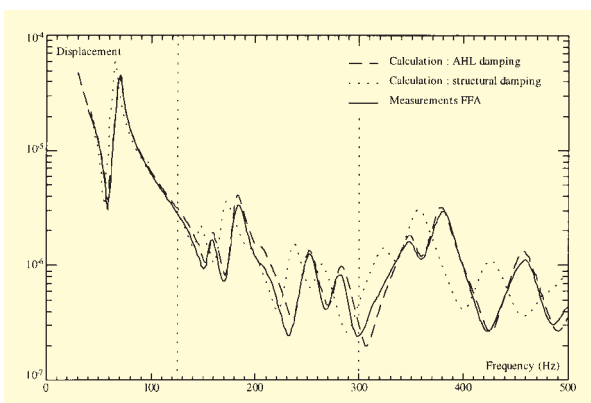


respectively. The modal damping is an average value for the whole structure. This means that local damping cannot be taken into account separately. To be able to take concentrated damping into account B2000 has been extended with the possibility to define a complex E- and G-modulus. This means that for each element a separate complex element stiffness matrix can be calculated and a complex global stiffness matrix can be assembled. This leads to complex eigenvalues from which the damping can be obtained by dividing the imaginary part of the eigenvalue by its real part. In the framework of a BRITE/EURAM project, the Swedish Aerospace Laboratory FFA developed a new damping model, the so-called 'Augmented Hooke's Law'. NLR implemented this model in B2000 to evaluate it. This damping model is frequency dependent and must therefore be solved iteratively. Responses can be calculated with the frequency response processor. At the Deutsches Zentrum für Luft- und Raumfahrt (DLR) a method to determine damping ratios of composite structures for separate ply and resin

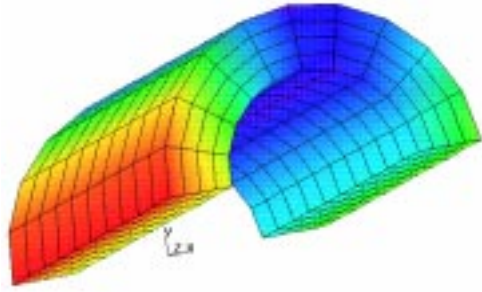
properties has been implemented which is based on the energy method. With the implemented method the influence of fibre and resin properties, fibre angles and stacking sequence on the damping ratio of a composite structure can be analysed.

### Thermal analysis

B2000 can be used for thermal analysis, too. There are shell and volume elements available to model the thermal conductivity in a material. Furthermore, special elements, the so-called Neumann elements, are available to define Neumann boundary conditions. This feature is used by NLR in the framework of a project 'Modelling of gas turbine components'. The intention of this project is to calculate thermo-elastic stresses in order to be able to predict the life time of a gas turbine component or the coating of a turbine blade. In a pilot study, an internally cooled thick-walled tube placed in a hot gas stream has been analysed. In B2000 the steady state temperature distribution has been calculated in which the heat transfer from the gas to the material and the material to the cooling air has been modelled with the Neumann elements. The same mesh can be used to calculate the thermal expansion and the thermo-elastic stresses. A time integration processor is being developed to be able to perform transient temperature analyses too. At DLR special composite thermal shell elements have been developed and B2000 has been extended with the capability of reading a radiation influence matrix created in NASTRAN. The radiation problem is solved with the modified Newton method.



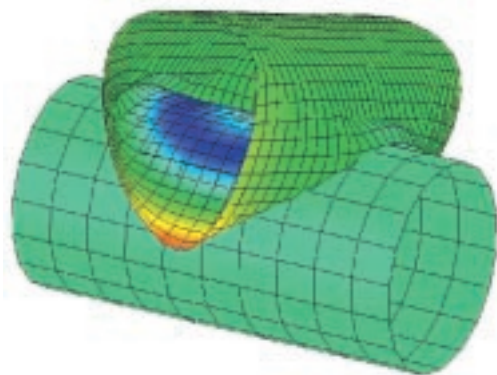
*Response of a point on a plate, calculated with two different damping models and measured*



*The steady state temperature distribution of a thick walled cooled tube in a gas stream, with the heat transmission coefficient varying in circumferential direction*

### Crash analysis

A completely new macro processor for crash analysis is being developed by the Delft University of Technology. It is to be an independent explicit finite element code, based on the database manager MEMCOM and using the same data structure as B2000. It is designed for studying the dynamic behaviour of structures, including (shock)wave propagation, stamping, dynamic post-buckling behaviour and crashing.



*Collision of two tubes, resulting in large plastic deformation*

Features currently available are:

- predictor-corrector time integration method;
- velocity instead of displacement boundary conditions;
- improved Belytschko-Tsay shell element;
- plasticity: the Besseling fraction model;
- Lagrange-like node-to-segment contact;
- computational restart.

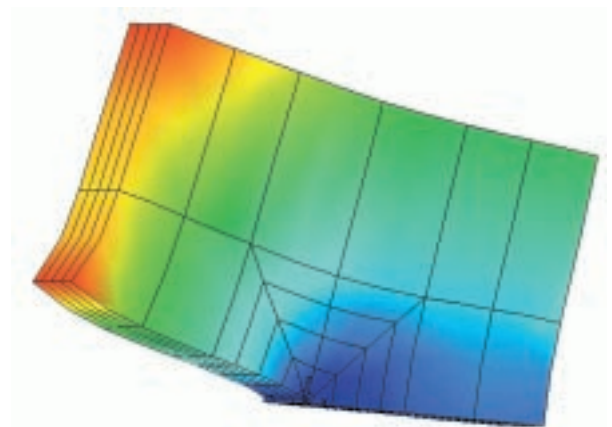
Because of the use of MEMCOM and the modular set-up of the code, the implementation of new features is relatively simple.

### Crack propagation

For the analysis of crack propagation B2000 has been extended with the processors B2LCP and B2CONTCRACK. The latter was developed at the Delft University of Technology.

The linear crack processor (B2LCP) calculates the Stress Intensity Factor (SIF) along a crack front using the Virtual Crack Extension method. An automated procedure to scan an arbitrary 3-D solid mesh for a crack front is part of this processor. This automated procedure performs the shift to be applied to the nodes and calculates the SIFs for all modes in the crack front, too.

In aircraft fuselages cracks are most likely to initiate in the longitudinal direction. Cracks which initially propagate in the longitudinal direction can turn into a circumferential line as a result of frames and other structural elements which change the stiffness locally. This change in crack growth direction is called flapping. Due to the cabin pressure, large deformations are observed near cracks in aircraft fuselages. Therefore the continuation processor B2CONT was extended to predict crack growth. This processor, called B2CONTCRACK, includes extension of the non-linear shell element for the calculation of the SIF and the elastic T-term. This is done with the mode enrichment technique. The elastic T-term is used to calculate the direction in which the crack will grow. On top of this an automated procedure was developed to generate a mesh which models the crack. This procedure includes mesh refinement at a new crack tip and generation of a coarse mesh around the crack far away from the tip.



*Deformation in a specimen with an edge crack*

## Conclusion

B2000, the highly modular code with its accessible database structure is very well suited to the needs of researchers. New algorithms, finite elements, material models, or (optimization) strategies can be implemented very easily. The Delft University of Technology, Twente University and the Swiss Federal Institute of Technology (EPFL) in Lausanne operate and contribute to the code. SMR, the supplier of the framework of B2000, applies the code for all kinds of special engineering problems and adjusts the architecture of the code to the latest developments in the field of computer science. NLR's sister aeronautical institutes Deutsches Zentrum für Luft- und Raumfahrt and Centro Italiano Ricerche Aerospaziale also use the code, which accommodates the exchange of software developments. NLR is pursuing a co-ordinating role in the development of B2000 and has already organized a first users conference.

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