Optimization of Aircraft C
Nonlinear Finite Element

Modern aeronautical structures are often made of composite materials and aircraft panels are no exception to the rule. As a consequence, the demand for powerful and efficient design tools increases and brings more and more challenging projects to the research and development community.

The optimization of composite panels is quite a challenge due to the inherent complexity of the analysis methods involved in the computational process and the type of responses required by the formulation of the optimization problems to be solved.

This article presents the implementation of recent research work – sponsored by the VIVACE European research project (see [1] and [2]) – and its application to an industrial test case at AIRBUS. This work is unusual in that the optimization problem solved combines linear and nonlinear finite element analyses in a unified computational framework where the evaluation of sensitivities allows huge time savings with respect to other strategies such as finite-differences schemes.

With the focus of this article being the application of the developed methods in an industrial framework, it does not describe the full details of the methodologies put in place to compute efficiently the analysis responses (these details can be found in [3] and [4], for instance). Rather, the targeted application at AIRBUS and the results obtained are presented.

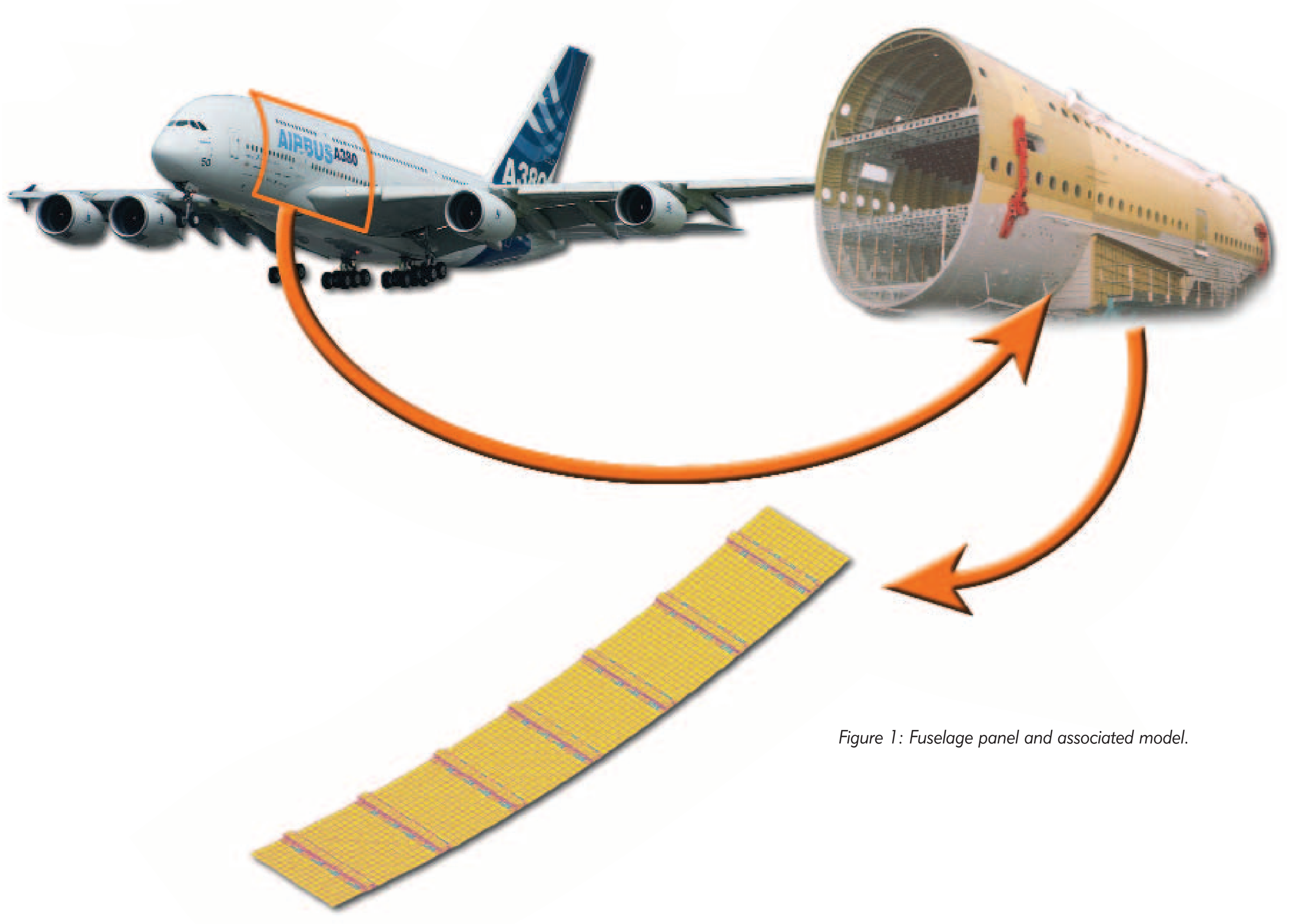

Figure 1: Fuselage panel and associated model.

Composite Panels with Analysis and Sensitivities

We consider the optimization of a composite fuselage panel made of seven so-called *super-stringers*, i.e. a stringer riveted to a skin panel. Figure 1 shows the whole panel and gives an idea of its location in a real aircraft. The considered stringers have a trapezoidal profile – they are also called Omega stringers (see Figure 2).

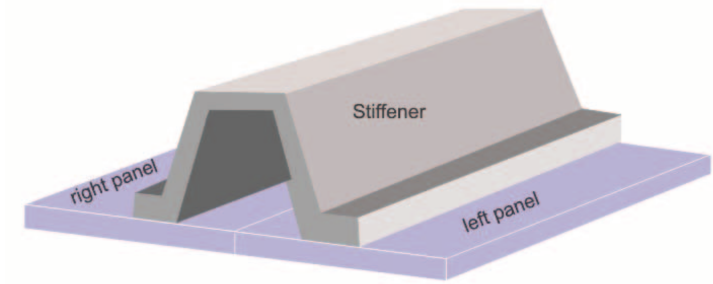

Figure 2: Omega super-stringer (stringer profile and adjacent skin panels).

A finite element model of this composite panel was first created with SAMCEF, which is part of the SAMTECH suite of general-purpose finite element analysis modules (see [5]). Note that the resulting model (shown on the right part of Figure 1) is relatively large since it contains up to 17000 nodes, 16000 cells and 110000 degrees of freedom.

The panel and the associated super-stringers are made of composite layers, each of them being defined by an orientation and a thickness (see Figure 3).

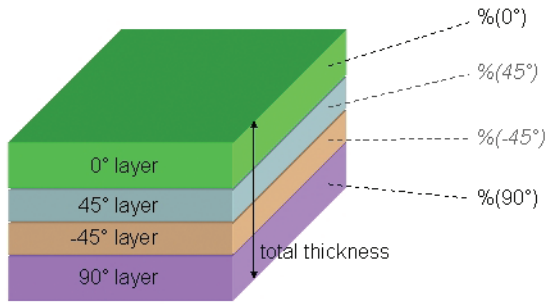

Figure 3: Composite layers and properties.

While the fiber angle is restricted to take four discrete values (0º, -45º, 45º and 90º), the thickness may vary continuously between some predefined bounds, which were set to 0.4 and 2 mm in this case. The goal of our application was to find the optimal values of the ply thicknesses for each orientation, for each one of the seven super-stringers, a distinction being made between thicknesses for skin panels and for stringers. Since it is assumed that the thicknesses for 45º and -45º plies are identical, this amounts to considering:

3 (orientations) x 7 (super-stringers) x 2 (skin panel + stringer) = 42 design variables.

The design parameters having been defined, it remains to specify the analysis responses we use as objective and constraint functions in the optimization problem.

The aim is to have the lowest possible weight; hence this will be the objective function – to be minimized. Constraints are formulated in the form of buckling and collapse reserve factors:

- the buckling reserve factor is a list of the first say n buckling modes resulting from a linear finite-element analysis; all values of this list must remain above some margin, which we may denote by $\eta_{buckling}$;
- the collapse reserve factor is computed by a nonlinear finite element simulation, and again its value is constrained to remain above another threshold value, denoted by $\eta_{collapse}$.

Depending on the chosen margin policy, $\eta_{buckling}$ and $\eta_{collapse}$ may take different values. Very often, $\eta_{buckling} = \eta_{collapse} = 1$.

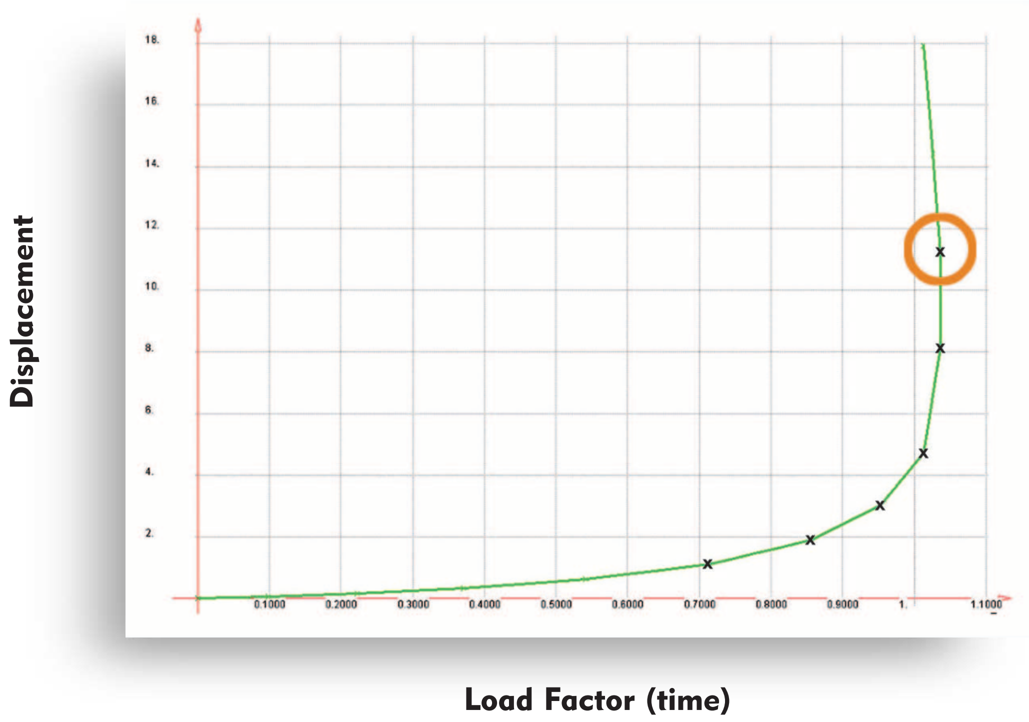

Figure 4: Displacement of a node as an illustration of the collapse.

Linear buckling analysis

The optimization problem having been defined, let us first briefly consider some issues related to the computation of the buckling reserve factor. By definition, the first buckling load is of interest when designing a structure to withstand instability. Theoretically, this single value corresponds to the $RF_{collapse}$ constraint. However, due to mode-switching, there is no guarantee that the first buckling load always corresponds to the same buckling mode. As a consequence the related sensitivities are not necessarily relevant for the subsequent steps and may cause erratic convergence. This is the reason why, instead of using mode-tracking techniques, a small set of say n buckling loads is often actually computed, the $RF_{collapse}$ constraint then being a vector-valued result as defined above. Since all these n constraints must now be satisfied, mode-switching inside those n values should not be an issue anymore.

However, in a recent paper (see [3]), it was demonstrated that the value of n must be chosen carefully. Indeed, if one chooses too low a value for n, it turns out that, at a given iteration, the buckling modes taken into account by the optimizer may only influence a small part of the structure, which will be designed, while the remaining structural parts are not sensitive. If repeated, this scenario leads to oscillations and deteriorates the convergence of the optimization process.

Taking larger sets of buckling loads was thus shown to be much more efficient both in terms of convergence and quality of the solution. For the application considered in this paper we took n =100.

Nonlinear analysis, collapse reserve factor and sensitivities

Next we investigate the nonlinear analysis and the computation of the collapse reserve factor. In SAMCEF Mecano [7] the sensitivities of the responses are available and can be transmitted in a straightforward way to the optimizer. While preserving the efficiency of gradient-based optimization algorithms, this allows huge time savings with respect to the class of approaches where the derivatives are approximated, and this is certainly one of the most remarkable achievements of the research and development work described here.

For the particular case of the collapse reserve factor, a specific strategy was put in place. Figure 4 illustrates the collapse of a super-stringer by depicting the load-displacement curve of a node belonging to the skin panel.

An obvious choice for the collapse RF is the load factor, which we denote by λ. In the example of Figure 4, we could take

$$RF_{collapse} = \lambda = t \approx 0.566$$

However this way to compute the collapse RF is not fully satisfactory since the sensitivity of λ is not directly available from a nonlinear analysis. Furthermore, the zone corresponding to the collapse often presents some numerical instability.

Hence we were led to the development of an alternative strategy, based on Riks' continuation method (see [8]): while classical Newton methods can have problems when passing a limit-point (because the generalized load

“…the sensitivities of the respo
be transmitted in a straightfo

displacement curve may have a decreasing time along the curve), continuation methods involve an additional parameter, namely the arc-length, which is controlled instead of the time. This was combined with the implementation of a dedicated computational mechanism ensuring that the gap $\Delta\lambda$ is orthogonal to the curve (rather than vertical), which further improves the accuracy of the sensitivity (see Figure 5).

Figure 6 shows the sensitivity curve of the load factor with respect to a ply thickness. The advantage of using a continuation method appears clearly in this context since the collapse can be identified as the load factor (simulation time) corresponding to the turn back point on the curve. As a consequence, post-processing of the nonlinear analysis will simply consist of getting the maximum of the simulation times (abscissa) and its sensitivities.

Optimization Session and Results

Having briefly described the computational schemes put in place to compute both reserve factors of interest in the framework of the targeted application, we now show their integration within a multidisciplinary optimization platform and the results of the optimization process itself.

The computational framework chosen for defining and running the optimization process is BOSS quattro, the open application manager for parametric design and optimization developed at SAMTECH (see [9] and [10]) allowing a complete integration of the software tools mentioned before for linear and nonlinear finite element analyses.

Building the optimization session is straightforward:

1. the finite element model is first imported in BOSS quattro;
2. the optimization variables (ply thicknesses) are selected from the list of available model parameters;
3. a complete computational process is then created, involving as many external tasks as the number of analyses: each task is fully defined in a separate window, where application options may be set (host, parallelism ...) and numerical results are properly defined;
4. the external tasks are connected to the optimization task and the latter is defined through a specific window: both the type of function (objective to be minimized, inequality constraint ...) and the (possible) associated bounds may be selected, together with similar information related to variables (bounds) and algorithmic options (convergence and admissibility thresholds, maximum number of iterations, …).

This is summarized in Figure 7.

Let us now come to the results that were obtained for the optimization of the composite fuselage panel described earlier in this text. Figure 8 gives an overview of the optimization process: starting from the main window of BOSS quattro, one can see some intermediate results obtained with both FEA tools we use (namely SAMCEF Linear and SAMCEF Mecano) until convergence of the process. The left pictures show displacements corresponding to the first buckling load while the right pictures show displacements at collapse.

Convergence was achieved after 27 optimization iterations, which is remarkably fast given the complexity of the underlying problem, the main CPU cost being associated to the nonlinear FE analyses.

The evolution of all three functions defining the optimization process (mass, buckling and collapse reserve factors) is also represented on three separate curves. It is worth noting that an overall mass decrease of 35% was achieved, both reserve factor constraints being satisfied (the lowest weight value was obtained at iteration 15 but this did not correspond to a feasible solution since the buckling constraint was violated).

Finally, the optimum values of thicknesses are represented using different colour ranges, showing a consistent distribution.

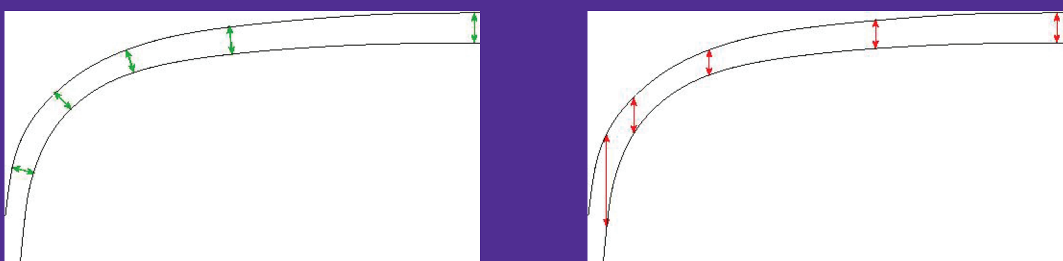

Figure 5: Vertical vs. orthogonal gaps on load-displacement curves.

onses are available and can
rward way to the optimizer. ”

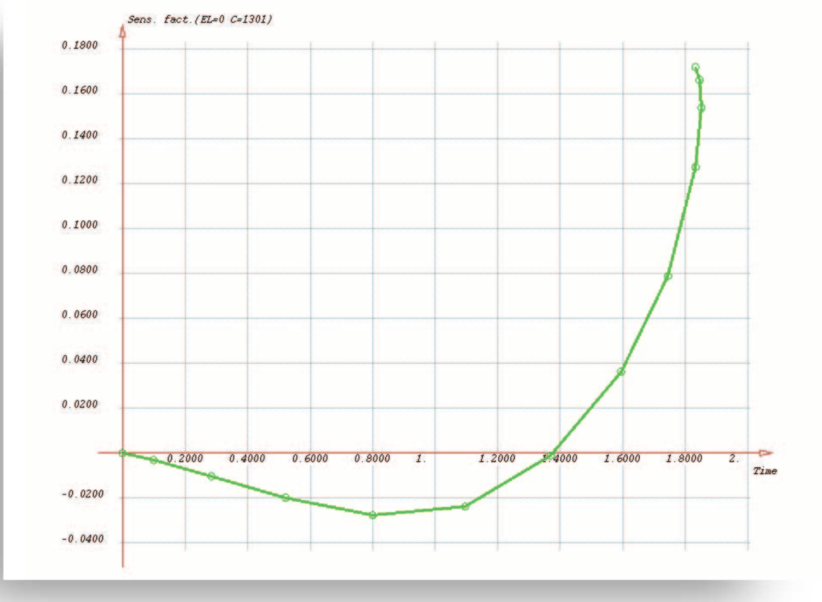

Figure 6: Sensitivity of load factor with respect to ply thickness.

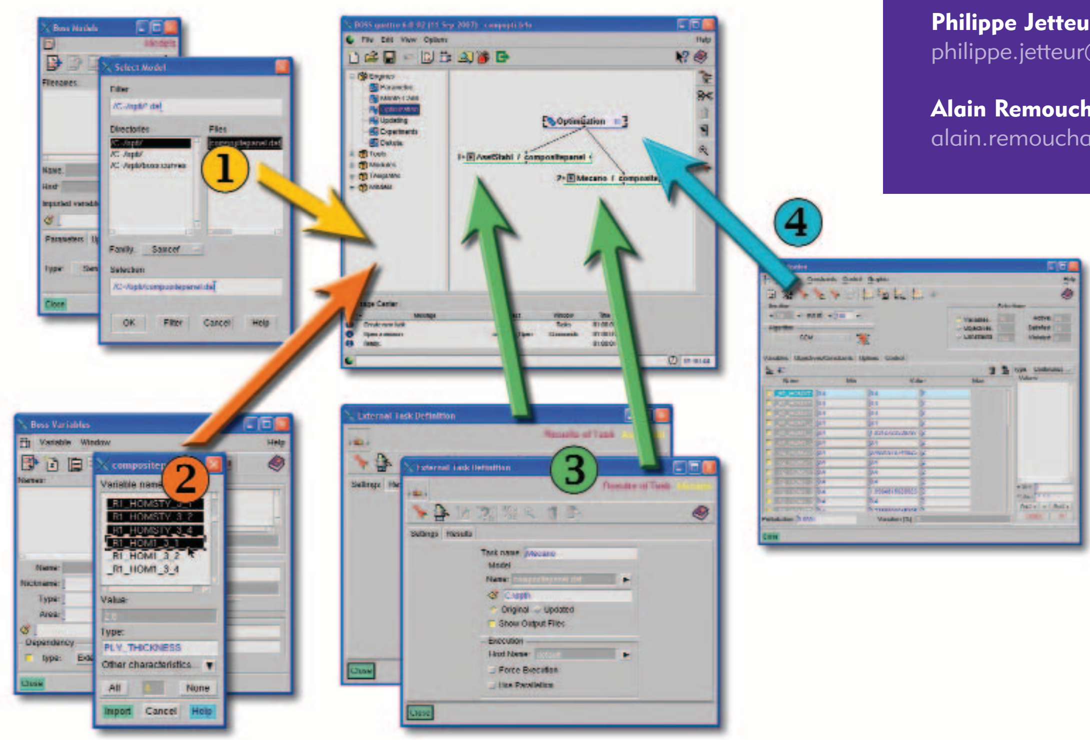

Figure 7: Creation of the optimization session with BOSS quattro.

Conclusions

The composite panel optimization scheme and results presented in this text show the efficiency of the combination of FEA tools able to simulate complex structural phenomena and to provide specific responses and their derivatives in a single run, which can be used advantageously in the framework of optimization. In particular, the most significant achievements are linked to the implementation of efficient computational schemes for the evaluation of reserve factors and the associated sensitivities, even in the nonlinear case. Altogether, those developments and their complete integration within industrial software packages provide the engineers with advanced analysis and simulation tools for the design of composite structures.

Contact

Benoît Colson
benoit.colson@samcef.com

Michaël Bruyneel
michael.bruyneel@samcef.com

Stéphane Grihon
stephane.grihon@airbus.com

Philippe Jetteur
philippe.jetteur@samcef.com

Alain Remouchamps
alain.remouchamps@samcef.com

“...classical Newton methods can have problems when passing a limit-point.”

> Convergence was achieved after 27 optimization iterations, which is remarkably fast given the complexity of the underlying problem.

References

[1] VIVACE Website: http://www.vivaceproject.com

[2] B. Colson, S. Grihon and A. Remouchamps. Advanced computational structure mechanics optimization. VIVACE Forum 2, Den Haag, 24-26 October 2006 and 10th SAMTECH Users Conference, Liège, 13-14 March 2007.

[3] M. Bruyneel, B. Colson and A. Remouchamps. Discussion on some convergence problems in buckling optimization. To appear in Structural & Multidisciplinary Optimization, 2008.

[4] B. Colson, M. Bruyneel, S. Grihon, Ph. Jetteur, P. Morelle and A. Remouchamps. Composite panel optimization with nonlinear finite-element analysis and semi-analytical sensitivities. NAFEMS Seminar on "Simulating Composite Materials and Structures", Bad-Kissingen, 6-7 November 2007.

[5] SAMTECH website: http://www.samcef.com

[6] SAMCEF Linear. http://www.samcef.com/en/pss.php?ID=4&W=products

[7] SAMCEF Mecano. http://www.samcef.com/en/pss.php?ID=5&W=products

[8] E. Riks, C. Rankin, F. Brogan (1996). On the solution of mode jumping phenomena in thin walled shell structures. Comp. Meth. Appl. Mech. Engng., 136, pp. 59-92.

[9] Y. Radovcic, A. Remouchamps (2002). BOSS quattro: an open system for parametric design. Structural & Multidisciplinary Optimization, 23, pp. 140-152.

[10] BOSS quattro. http://www.samcef.com/en/pss.php?ID=3&W=products

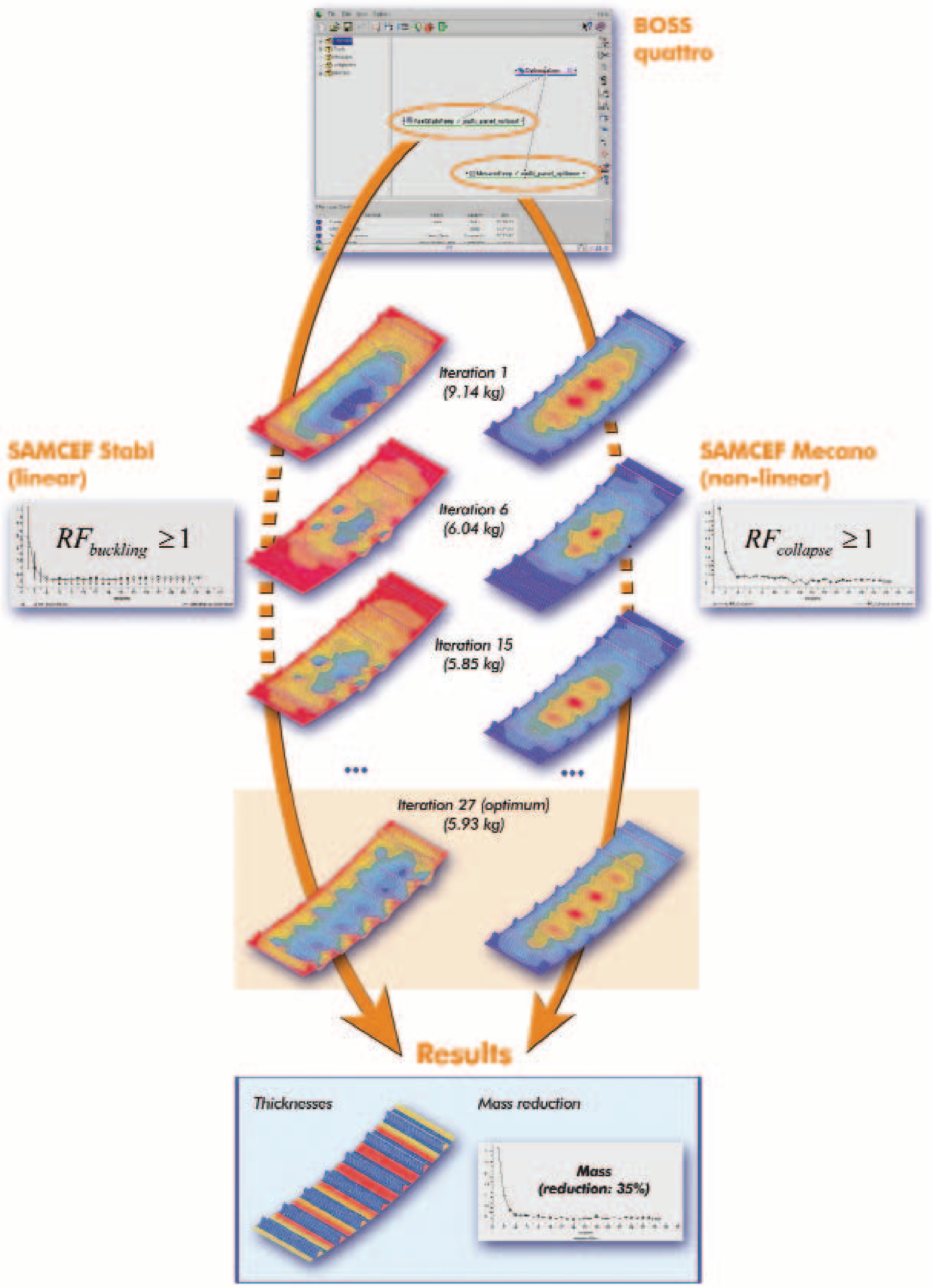

Figure 8: Optimization session in BOSS quattro and associated results.

Creating Awareness | Delivering Education | Stimulating Standards

NAFEMS

NAFEMS is the International Association for the Engineering Analysis Community, an independent, not-for-profit, international membership association, owned by its members. The scope of its activities encompasses all simulation technology, including Finite Element Analysis and Computational Fluid Dynamics. As new application areas and techniques constantly evolve, NAFEMS becomes involved to create awareness and deliver appropriate education and training.

NAFEMS publications and benchmarks are widely regarded within the engineering analysis community as the most authoritative source of information available. The areas covered by NAFEMS are expanding year by year with the growth in membership, and people increasingly view NAFEMS as a one-stop shop for all aspects of information on engineering analysis.

For engineering analysts, NAFEMS offers an excellent platform for continuous professional development.

Get Involved.
Join NAFEMS Today.

Nasmyth Building • Scottish Enterprise Technology Park • East Kilbride G75 0QR • Scotland, UK
T +44 (0)13 55 22 56 88 **F** +44 (0)13 55 24 91 42 **E** info@nafems.org **W** www.nafems.org