VALIDATING NOVEL STIFFENED PANEL CONFIGURATION GENERATED WITH TOPOLOGY OPTIMIZATION USING NON-LINEAR ANALYSIS

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Context

Topology optimization (TO) is an optimization approach that seeks to reduce weight of structural components and improve stiffness by proposing new material configurations [1]. One of the current challenges identified in industry is using TO for the design of complex structures, such as wing panels, where the main design concerns are typically buckling, instabilities and fatigue [2]. Our research team in collaboration with Stelia Aerospace develops methods to integrate TO into the design process by considering buckling and instability constraints which has been shown to be a challenge [3]. It is worth noting that fatigue concerns are not considered in this project. This paper will address the need for a validation methodology for novel structural configurations.

Current structural analysis methods are based on a well-studied ortho-grid configuration which consists mainly of a panel with an orthogonal stiffener pattern [2]. The typical structural analysis for this kind of panels is carried with semi-empirical formulas. However, for non-conventional stiffening configurations, there is no empirical data available, which makes the semi-empirical formulas non-applicable. As such, we found that a non-linear analysis is an effective solution to validate the buckling resistance and the stability of new stiffener configurations. Nonlinear analysis leverages the flexibility of finite elements and a precise post-buckling modeling; however, it comes at a high computational cost.

For our case study, we used preliminary version of the upper skin of the wing of an existing business jet, as illustrated in Figure 1. This studied panel was selected due to its high compressive loads and identified critical buckling margins. We used the nonlinear solver of the Hyperwork Suite, RADIOSS [4], as we were already using the Hyperwork Suite for both topology and size optimization [5]. The software uses the arc-length method to implicitly calculate each timestep of the nonlinear analysis.

Validation of the nonlinear model with semi-empirical formulas

For the validation of the results between semi-analytical calculations and FEM results, same modeling hypothesis are used for both. As such, the detailed model is considered flat with no curvatures and of the same thicknesses and the same stiffener pitch (Figure 2). Concerning the loading, axial and transverse compressive loads are considered in addition to the shear load. The axial compression is applied on rigid elements and while the other loadings are applied with distributed forces. The mesh used is CQUAD4. The boundary conditions are used to represent the "infinite" conditions on all sides, and the ribs are modeled with out of plane displacement constraints. Finally, the material applied for the test case is a standard aluminum, with the nonlinear clad material properties considered.

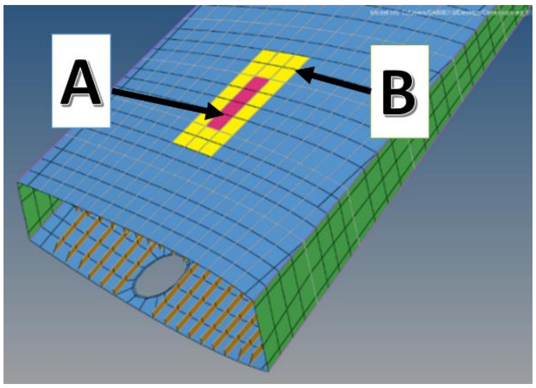

Figure 1 Studied skin bay [A] and half-bay [B] on the GFEM.

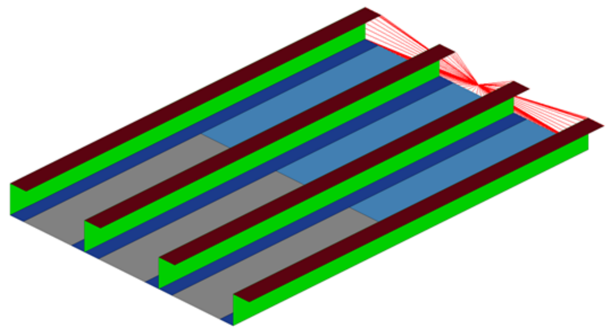

Figure 2 Studied skin bay detailed FEM

For the chosen test case, the calculated margin of security is of -0.03 with the semi-empirical method, with the buckling of the cut-off being the limiting factor. This margin is standard, as the goal is to have a margin close to zero. The FEM linear buckling of the panel is calculated at 1.08 time the ultimate load.

A graph of the nonlinear run is shown in Figure 3, where the stress of a skin and a stiffener element is shown for both extreme layers of the finite element. In the graph, the buckling is shown when the upper and lower side of an element diverge due to the bending of the element. After the buckling, the analysis shortens the time step to model the post-buckling regime, it stops when the time step required becomes too small. The deformation at the end of the analysis is shown in Figure 4.

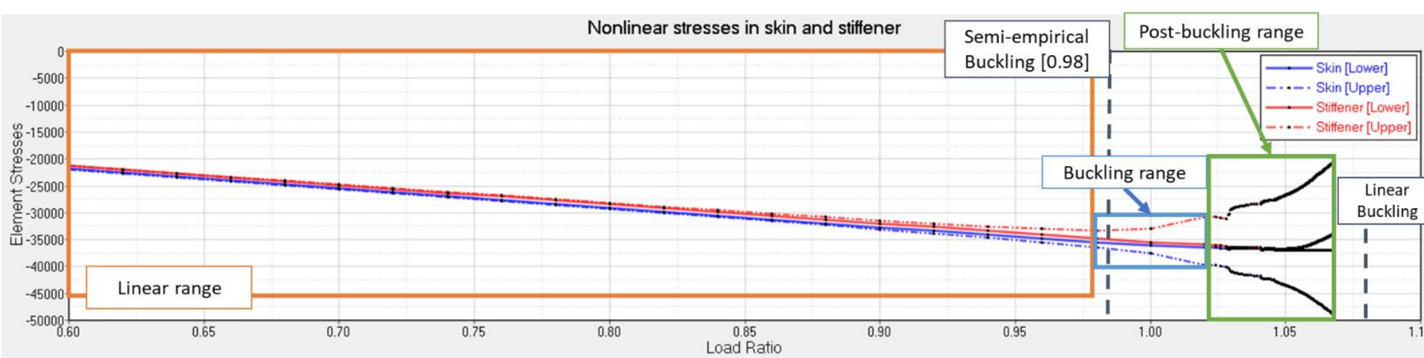

Figure 3 The evolution of stress in the skin and stiffeners of the panel during nonlinear analysis

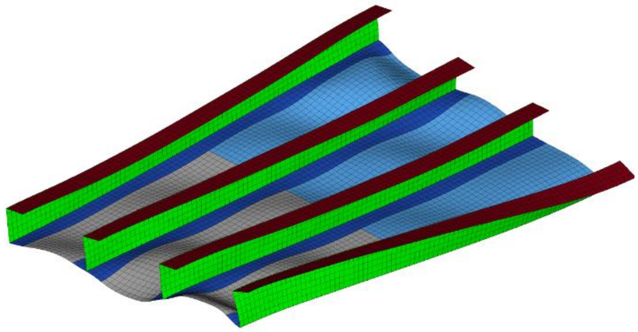

Figure 4 Nonlinear deformations at 1.07 time the ultimate load

The analysis shows that the first section is indeed the linear range of the analysis, which is from 0 to 1 time the ultimate load, as expected. We can see that the panel starts to become unstable at around the ultimate load, just as predicted by the semi-empirical analysis. Furthermore, both analyses have found the same failure mode i.e. the buckling of the cut-off of the stiffener. This is the first step to give us confidence in the nonlinear analysis; physical tests will be required for the validation of novel stiffening configurations.

The nonlinear result also shows that predicting the failure of a stiffened panel using only linear properties is not straightforward. As the linear buckling doesn't take material nonlinearities into account, it will over evaluate the rigidity of the structure when near the plasticity limit of the material. The combination of the two makes the failure occurs before plastic yield and before linear buckling. This emphasise the importance of nonlinear analysis to validate the optimization results. One recalls that the optimization is based only on linear constraints.

Using nonlinear analysis on novel stiffener configuration

The goal of the nonlinear analysis is to study non conventional patterns of stiffeners. The section above discussed the correlation of nonlinear analysis and semi-empirical formulas for a conventional panel. The present section uses an interpreted pattern obtained with topology optimization. Figure 5 illustrates a result of topology optimization for linear stiffness and mass with a buckling constraint; it shows an optimized load path in red. Including buckling constraints in topology optimization is still an open research question, which is one of the drivers of this work.

This information is interpreted as an optimized stiffening pattern, as shown in Figure 6. The optimized stiffening pattern may then be used in a sizing optimization to minimize mass while linear buckling and static stress constraints are active. The sizing is then validated using the nonlinear analysis. This allows one to validate the optimization results, where it may be observed that the performance is achieved; the nonlinear analysis shows the structure should withstand at least 1.05 time the ultimate load, with a buckling as illustrated in Figure 6.

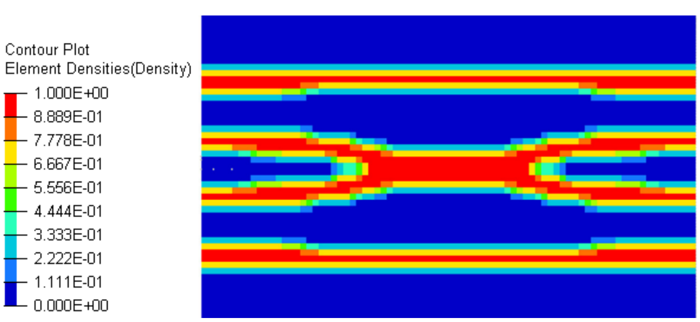

Figure 5 Topology Optimization result for the test case

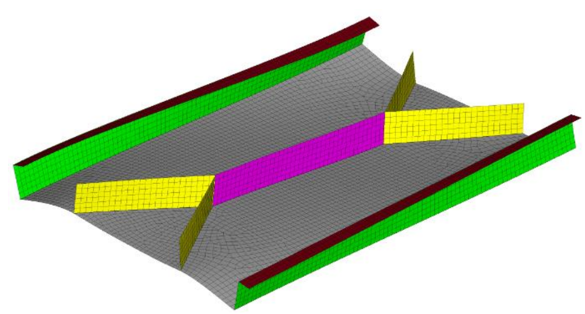

Figure 6 Interpretation of the topology optimization and nonlinear deformation [1.05 ultimate load]

Conclusion

Our current results illustrate the importance of validating the nonlinear effects, such as buckling and material plasticity when assessing the performance of stiffened panels through a rigorous methodology. The nonlinear finite element analysis allows the stress engineer to validate all stiffening patterns based on different interpretations of topology and sizing optimization.

Furthermore, our current results show the importance of the nonlinear analysis when linear buckling and material plasticity occur at about the same load. This gives us insight on how to push our topology and sizing optimization processes in the future. Future work includes applying a data-based approach to inspect the topology design space in an automated fashion [6].

References

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