

Assessing Structural Integrity of Airborne Targets in Vulnerability Simulations

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ABSTRACT

Structural integrity is even more important for survivability of aircraft than for other platforms, because it must support all other primary factors, i.e. lift, thrust and control. Aircraft structure differs significantly from other systems as the level of redundancy is not a fixed integer but rather may be expressed as a real-valued reserve factor. This makes structural integrity difficult to assess in classic vulnerability codes that calculate kill probabilities on component level and use fault trees to assess the overall consequences.

Several methods for assessing structural integrity will be briefly discussed, and as none of these methods is alone able to satisfy the requirements of stochastic vulnerability analysis, a combination of methods will be proposed based on a finite element model of the complete aircraft structure and potentially making use of Bayesian Networks to expand results of vulnerability analysis to more distinguished statements.

1.0 INTRODUCTION

According to Prof. Ball’s famous text book on Aircraft Combat Survivability [1] there are four essential elements for the survivability of aircraft – lift, thrust, control and structural integrity. The latter is of prime concern, because the aircraft structure must remain sufficiently intact to make the other three effective and therefore structural integrity is even more critical for airborne targets than for any other platform.

Understanding structural damage is not only important on a small scale level, i.e. penetration damage and resulting failure of individual structural members, but it is also necessary to assess the total damage suffered by the overall structural assembly against the basic strength requirements of the target platform.

Failure criteria for components of “normal” systems – avionics, electrics, hydraulics etc. – can be regarded as being binary, i.e. a pipe is pressure tight or is not. Thus, the modeling of fault trees and consideration of

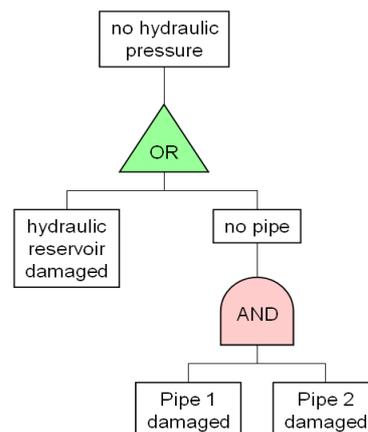


Figure 1: Example fault tree for a “normal” system

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redundancies is rather straight forward using Boolean Operators like NOT, AND, OR etc. (Figure 1).

For the structural system the situation is more complex, because individual components as well as the overall assembly react adaptively in a non-linear way – loading is re-distributed according to the new distribution of stiffness in the damaged state (Figure 2).

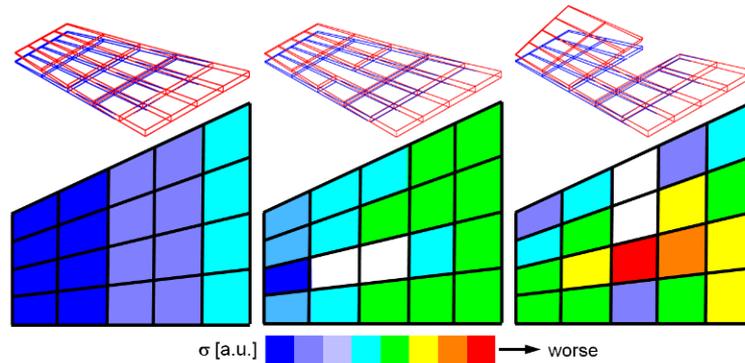


Figure 2: Example wing structure showing dramatic overall influence of damage locations

Most designs take benefit of this behavior resulting in a desired level of damage tolerance, e.g. the concept of a multi-spar wing tolerating total severance of a single spar without catastrophic failure. But what is the limit of tolerable damage, especially if there is a non-inherent combination of damages that is caused by external threat effects? Whilst the analysis effort for certification of the undamaged structure against a fixed set of load cases is already considerable, a full a-priori analysis of arbitrary multiple damages would be impossible to perform due to the huge combinatory number of cases (Figure 3).

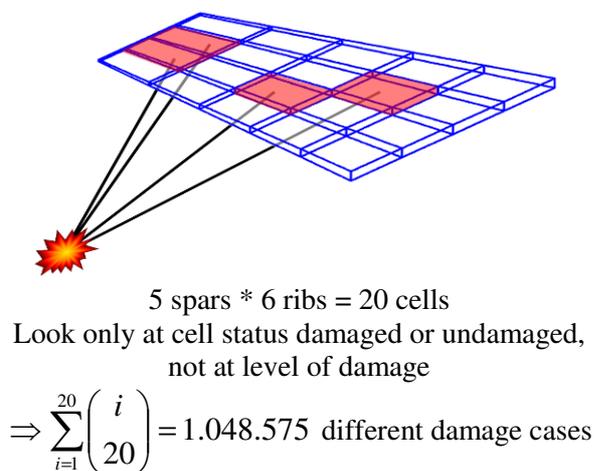


Figure 3: Calculation of possible damage combinations

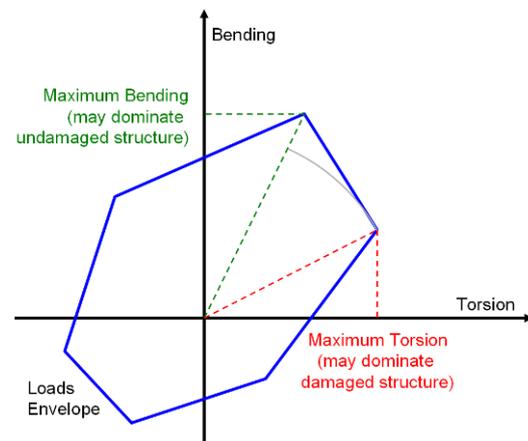


Figure 4: Loads envelope

In addition, design and sizing of structural components is based on a variety of load cases (Figure 4), extracted from different mission profiles with different maneuvers and configurations and thus differing in magnitudes and orientations. Often there is a dominant load case with a low probability (e.g. an extreme gust loading), which absence is resulting in a comfortable safety margin allowing to accept a considerable amount of damage before uncontrolled failure occurs. But there is also the possibility that for the damaged

structure a previously non-dominant and nominally much lower load case results in catastrophic failure. So the failure criteria are not fixed in general and damage defines restrictions in maneuvering, which may be acceptable or not in a given mission. And the reality is even harder to analyze, because substantial damage may also change the aerodynamics and thus the aircraft's control and resulting load cases themselves. Yet to speak of dynamic and catastrophic phenomena like flutter.

The following will provide a brief review of assessment methods for structural integrity within vulnerability simulations and will outline a proposal to tackle this problem in future developments – a proposal open to international collaboration.

2.0 POTENTIAL ASSESSMENT METHODS

2.1 Exclusion

Quite a common “method” is the explicit exclusion of structural integrity from the assessment of weapon effects or target vulnerability. But even if this assumption could be justified on basis of a forensic data base of past events, new target systems may have tighter limits for acceptable damage and a higher degree of interference between the structural system and e.g. the control system of an aerodynamically neutral or instable A/C. In addition, if there are no validated models to evaluate the contribution of structural integrity to overall vulnerability, how can the statistical significance of past events be demonstrated? Therefore, ignoring the problem cannot be an appropriate method for future assessments.

2.2 Empiric Models

Empiric models are first steps towards scientific solutions: Given evidence from past events, from specific experimental tests or any collection of more or less applicable data, we can try to find some order in the data and relate direct or calculated key results to key parameters of the threat and its engagement. A good example of such an empiric model is presented in [2], providing residual stiffness and strength of sections of a composite wing box against the number of hits from a fragment warhead in that section (Figure 5).

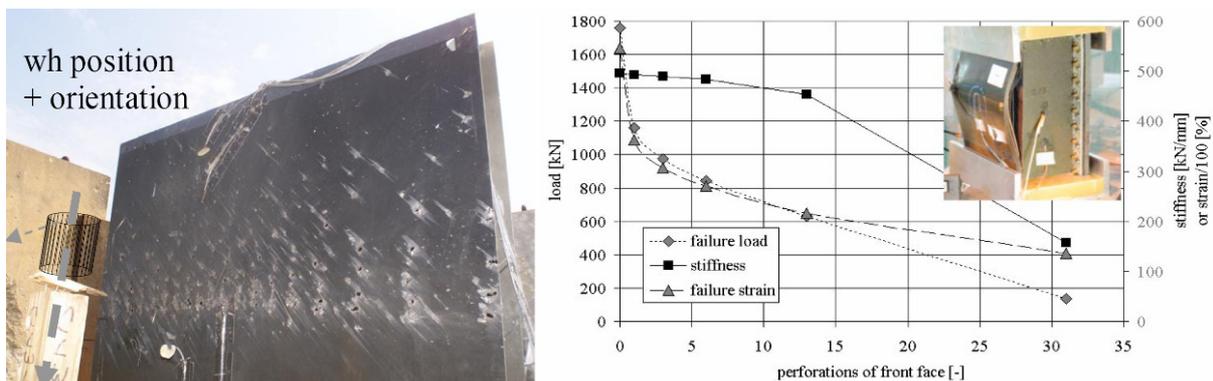


Figure 5: Example of an empiric model for composite survivability against fragments [2]

If there are no experimental data then numerical simulation can be a substitute: The concept mentioned in [6] uses global maximum von Mises stress (→ material failure), maximum wing tip displacement (→ effective bending stiffness) and maximum wing torsion (→ effective torsion stiffness) to define a damage index for a given damage case and a respective criterion (damage index > const) for wing failure due to insufficient strength or stiffness (← flutter). With limited effort a number of systematically selected and random operational damage cases can be defined and analyzed with finite element (FE) methods. From

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this analysis a wing sensitivity map may be created with weighting factors that reflect the relative importance of a cell for structural integrity. By simplifying this map to a small number of damage zones, in which all cells are assigned the same weighting factor the number of combinations of $N(Z)$ damaged cells in zone Z can typically be reduced to less than 50 (from 1 m cases for the combinations of individual cells). The extent of the zones and the respective weighting factors are chosen such that the weighting sum of the damaged cells of any case matches best the damage index (from FE analysis) of this case. At the end we find a critical weighting sum that is correlated to the critical damage index and thus any hit pattern resulting in a weighting sum higher than the critical one is assumed to represent a wing failure (Figure 6). If the weighting factor of a cell can be included in the target description as an attribute then this method can be easily implemented in a vulnerability code. If on component (cell) level only the kill/survival information is available, then a further step is required in order to map this criterion into the fault tree.

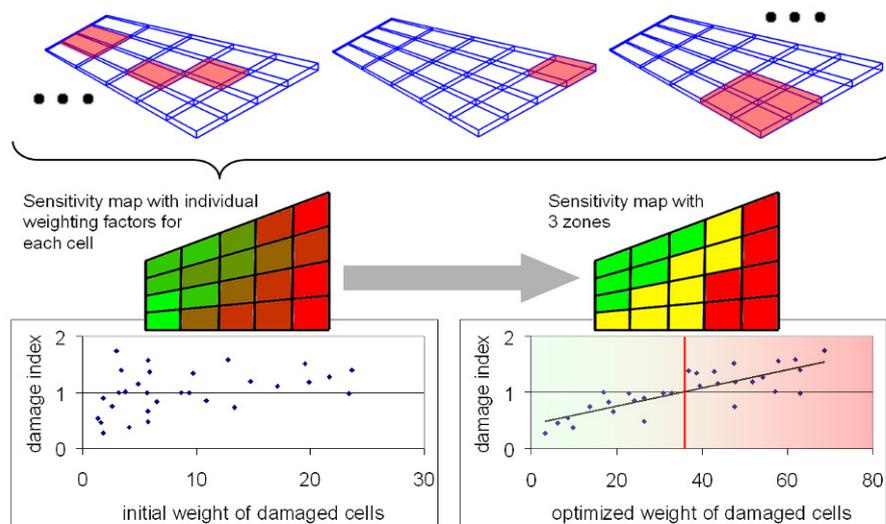


Figure 6: Sensitivity map and critical weight of damaged cells

However, empiric models are based on analytical formulas with some fit parameters and therefore are easy to implement into a vulnerability code. Unfortunately, they are strictly valid only for the data and cases on which they were built and any extrapolation to other types of structure is doubtful.

2.3 Engineering Handbook Methods

Having understood the limitations of empiric models the logical next step is to perform structural analysis using engineering handbook formulas allowing a more general application of respective models. Unfortunately, analytical solutions are often limited to geometrically simple cases like a flat plate with one or two circular holes in the middle and specific loading (Figure 7). Therefore complex-shaped structures with arbitrary damage patterns have to be mapped to those cases described in literature, rendering respective results (stress), to be estimations of a lower or upper limit.

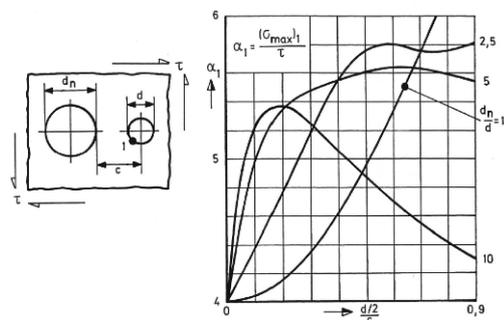


Figure 7: Stress concentration factor [3]

Furthermore, those formulas rarely cover non-linear effects, neither in geometry (deformations) nor in material (plasticity), yet to speak of non-isotropic material properties like for fiber composites.

There are advanced models [4] formulating damage size on basis of the dimension of the impacting object, the extend of damage it creates on the impacted surface, the thickness of the impacted panel compared to the dimension of the impactor, the impact velocity compared to the ballistic limit velocity of the panel for that impactor, the impact angle, the density of impacts regarding time and space (synergistic effects) and uniformity of the hit distribution. From that, the accumulated damaged area of all hits can be related to the total area of the panel and a residual strength can be read from a table being specifically developed for this kind of panel. On basis of the residual strength the probability of failure can be found from another table, potentially reflecting the relative frequency against the load case and amplitude. However, many assumptions are included in such a model and full validation would require a large number of experimental tests or validated FE calculations for each combination of panel type and applicable load case in the target. And still a huge uncertainty will remain, because the detailed pattern and orientation of the damage against the dominating load is crucial (Figure 2) but not included.

Thus, engineering handbook methods will be easy to implement but it will be hard to assign target components correctly to those methods and even harder to validate methods and assignments in general.

2.4 Damage Accumulation vs. Survivor Rule

Even if a single damage could be meaningfully described in the vulnerability model of the target, the question remains already within a single plate how to assess multiple damages. Damage accumulation as described above is the physically correct way but needs some attention concerning the correct handling of overlapping and near boundary damage. A much simpler alternative is accumulation of probability using the Survivor Rule $P_N = 1 - (1 - P_1)^N$, which calculates the failure probability of N events from the probability of a single event. Although this rule is often used without further analysis, it is only valid for independent events, i.e. for each event (shot) we assume a pristine population (an identical, new and undamaged target). Clearly, this assumption is not correct concerning structural integrity and multiple damage sites. Especially, it completely fails in cases of redundant components:

Let $P_H = 4/20 = 0.2$ be the probability of hitting one of the 4 attachment cells out of the 20 cells of the example wing and let P_A be the single shot wing failure probability caused by any of the attachment cells being hit.

Then firing 4 shots, the Survivor Rule would calculate a probability of wing failure of $1 - (1 - 0.2 * P_A)^4$, depending on P_A as shown in Figure 8.

Actually, failure occurs only if all 4 cells are hit and the probability of this hit pattern is independent of P_A

$$\binom{4}{20}^{-1} = 1/4845 = const \approx 0.0002$$

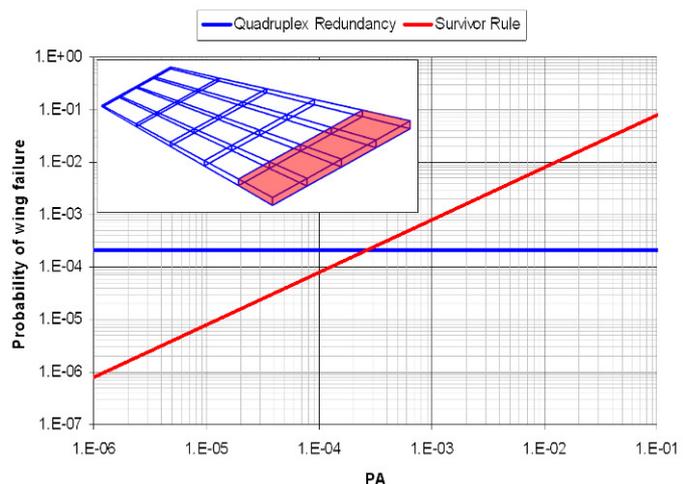


Figure 8: Comparison of Survivor Rule and actual failure probability of quadruplex redundant components

Only one specific value of P_A will reproduce this result and in general the common approach to incorrectly

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mix damage status with failure probability will be wrong, i.e. having hit 1 out of 4 crucial cells is not a 25% kill probability. However, we cannot deny that the Survivor Rule's resulting failure probability is often in line with engineering judgment and outlines the correct tendency, whereas more physical engineering formulas may not have a significantly higher level of confidence due to incorrect representation of the given case.

2.5 Neural Networks

Artificial neural networks mimic biological neural networks using a network of cascading parametric functions (often nonlinear weighted sums), which parameters can be adapted in a training phase to make the network resemble a given behavior.

In more practical terms neural networks are non-linear statistical data modeling tools. They can be used to model complex relationships between inputs and outputs or to find patterns in data. They have proven their ability to model deterministic laws with stochastic scatter – even in real time applications like flight test data processing. Using commercially available or even Open Source software, this concept could also be used to identify and implement the influence of arbitrary damage on structural integrity without explicitly modeling the underlying physics (Figure 9).

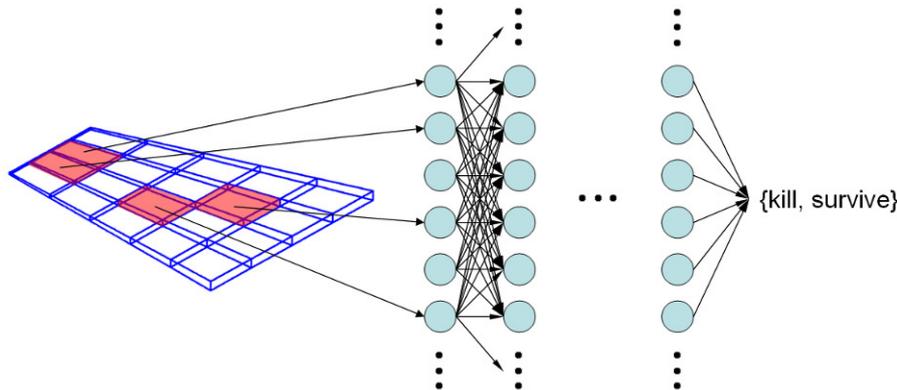


Figure 9: Fault tree for wing attachment

There are different algorithms for implementing the learning of the network, i.e. how to establish an optimum set of parameters. One of the most promising approaches is the Bayesian Neural Network, which uses distributions for the parameters and consequently produces distributions for the output, thus also giving information on the uncertainty of a result. Unfortunately, in any case the quality of such a network heavily depends on the amount of training data, which means again conducting large numbers of experimental tests or validated FE calculations.

2.6 Fault Tree Methods

In some cases the total effect of combined damage of different structural components is obvious and can easily be described by means of classic fault trees, e.g. the failure of 2 adjacent out of 3 wing attachments will lead to a loss of the whole wing (Figure 10).

However, for the majority of damage combinations, the consequences are not clear without further detailed analysis. As such a-priori analysis is not affordable (in the order of 10^6 cases), simplifications have to be established reducing the number of cases and making the resulting failure logic accessible to fault tree methods.

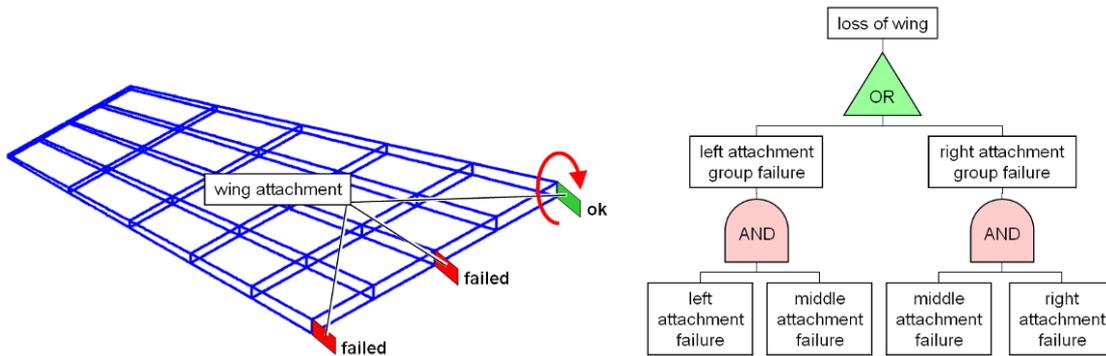


Figure 10: Fault tree for wing attachment

The elliptic criterion tries to separate basic failure modes and to set up a simple formula for combined cases: Let's assume that a limited effort of detailed analysis has demonstrated that the example wing can tolerate loss of 2 spars but not of 3 and loss of 3 ribs but not of 4 – given that all other parts, respectively, are undamaged. Then an elliptic kill criterion could be established of the form $1 \leq (N_{\text{Spars}}/3)^2 + (N_{\text{Ribs}}/4)^2$ resulting in a kill condition for failure of 2 spars and 3 ribs, but survival for failure of 2 spars and 2 ribs (Figure 11). If there is no possibility in the code to define functions in the fault tree, then a LEAST(N,M) operator, being true if at least N out of M input events are true, enables an implementation of this criterion. This approach could be extended to 4 dimensions in order to consider also failed skin elements of upper and lower skin. However, it wouldn't take into account the location of failures and thus had to be complemented by further criteria, e.g. that no 2 adjacent spars must fail at the same lateral position.

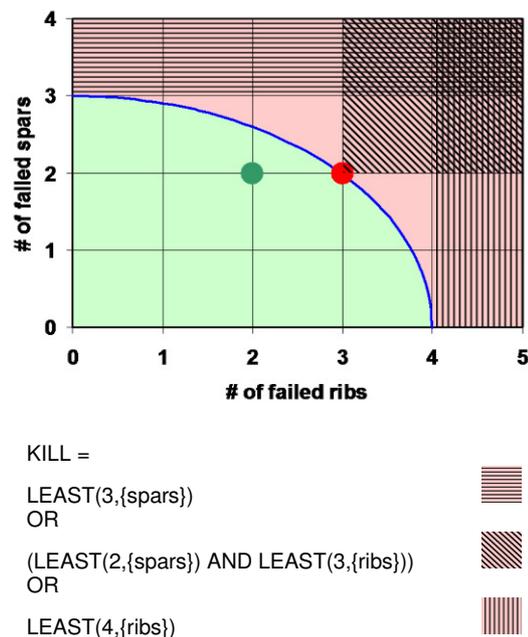


Figure 11: Elliptic criterion

Also empiric methods like the sensitivity map and weighting sum described before may be implemented this way in terms of failed components. The challenge is to define a discrete space spanned by mutually exclusive subsets of the components, e.g. the number of failed ribs/spars or the cells in damage zone 1-3 of the sensitivity map. The empiric method defines then a subspace in which the kill-criterion is true (Figure 11, red area) and this subspace has to be approximated by logic conditions expressed with the available operators (LEAST, AND, OR in Figure 11). Depending on the complexity of the empiric method, the solution of this problem is not trivial and may result in very large branches of the fault tree.

2.7 Bayesian Networks

The term Bayesian Network must not be confused with the above-mentioned Bayesian Neural Network. In principle a Bayesian Network or Belief Network has a fixed structure to be modeled by the analyst – although there are methods to learn complex structures from evidence data.

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Bayesian networks are specific decision networks and are formally defined as directed acyclic graphs whose nodes represent variables, and whose arcs encode conditional independencies between the variables. According to Bayes' Theorem of inference, the probability of A given B is related to the probabilities of A, B and B given A by $P(A|B) = P(B|A) P(A)/P(B)$. This enables the analysis (including sensitivity) of consequences for events of interest (e.g. failure on system-level) if evidence is given for a number of nodes (e.g. failure of components due to threat effects).

More practically Bayesian networks can be seen as an extension of the classic fault tree in the sense that it is not necessarily of hierarchical order, may have multiple but acyclic connections between nodes and that a node may have many discrete states. However, restricting the number of states to 2 (yes/no), ordinary fault trees with Boolean operators can be modeled (Figure 12). For more than 2 states generalized "Boolean" operators can be defined as one possibility of the general property matrix of a node (Figure 13).

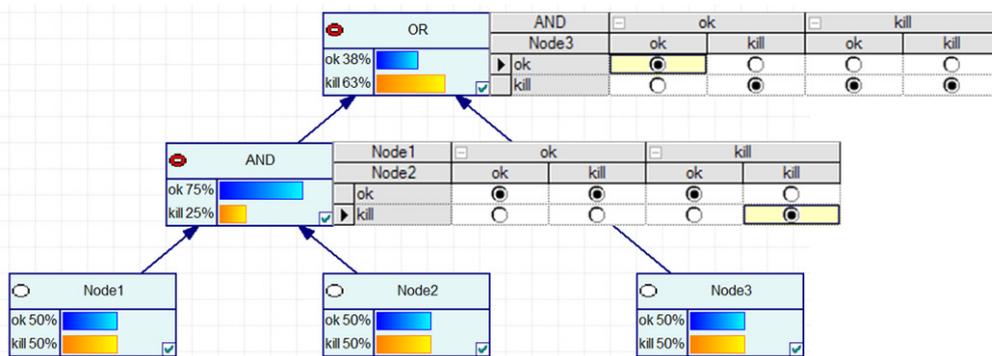


Figure 12: Bayesian Network modeling a binary fault tree with AND and OR [5]

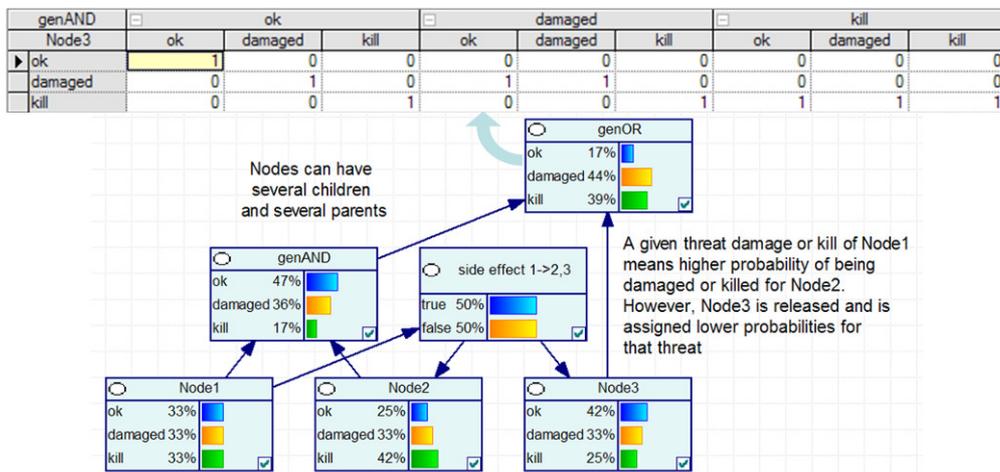


Figure 13: Bayesian Network with 3 states, generalized AND/OR and side effect [5]

Applied to structural integrity problems, Bayesian Networks could offer more flexibility in describing the interaction and combined effect of failure of different structural components. They could enable a more distinguished assessment of the severity of damage and its consequences on A/C-level, e.g. by giving probabilities of applicable g-load restrictions instead of the binary statement kill or survival. However, such application still needs to demonstrate that the benefit of more output detail actually justifies the increased effort in modeling.

2.8 Finite Element Methods

In principle, solving numerically the basic differential equations is the only way to do a valid analysis how a given damage influences the structural integrity. The most developed methods to do so are finite element (FE) methods. Ideally the analysis is based on a highly detailed geometry model of the target (\rightarrow high mesh resolution) with validated material models and failure criteria. The time-dependent problems of damage creation by threat effects and damage propagation in a dynamic loading situation can be solved explicitly. Coupling the structural model with computational fluid dynamics (CFD) enables to cover aero-elastic effects. Advanced fluid-structure-interaction (FSI) may also include blast and hydrodynamic ram effects (Figure 14). Even electromagnetic effects from high energy laser could be tackled with appropriate multi-physics FE codes.

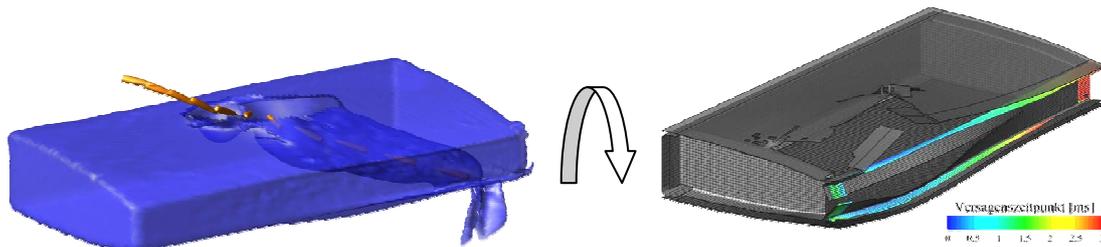


Figure 14: Example of coupled explicit FE – 12.7 mm against section of MALE wing tank [7]

Unfortunately and for the time being, this is only an outlook: Whilst most aspects have achieved a high level of maturity, there are still many open issues that prohibit these methods to be used in stochastic vulnerability analysis:

- Material laws and especially failure criteria for composite materials are a matter of research and satisfactory results for damage creation, propagation and final extent are only achieved in specific cases. Often the number of physical tests required to find appropriate parameters for new material laws is in the same order than the number of tests required for material qualification.
- There are many ways to model fluid-structure-interaction. None of them proved to be able to represent correctly all aspects found in experimental tests [6] – although it should be mentioned that the experiments also suffer from uncertainties in instrumentation, especially concerning pressure transducers for shock waves.
- The most striking obstacle is computational effort. To calculate a single case in the above-mentioned extent would take many weeks on a modern desktop computer. Thanks to parallelization and exponentially growing super-computing performance this may be compressed to the order of 5 minutes in the near future. But calculating kill probabilities for 26 different engagement directions in space, each over a grid of 100 mm for a \varnothing 10 m target and using 100 shots per grid with variations of shot line position in grid, threat velocity etc. – that means in total 26.000.000 calculations or about 250 years.

However, past experience tells us that no experiment should be performed without parallel simulation and vice versa. The benefits of FE methods are invaluable in guiding experiments by preliminary simulation of variants, in enabling insight by reproducing experimental results and in expanding results into areas not experimentally accessible or affordable.

Linear implicit FE calculations are validated, computationally efficient and well understood in their limitations. In the development process of aircraft this method is widely used and also applied to dynamic areas (e.g. fatigue) by using specific load cases. For certification issues the resulting stresses are compared

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to material allowable stresses and local reserve factors ($RF = \sigma_{\text{Allowable}}/\sigma_{\text{max}}$) are calculated. No $RF < 1$ must be present against the ultimate load (typically $1.5 \times$ limit load for normal operation). Although the method is restricted to small deformations and respective stresses without failure criteria, damage can be modeled explicitly by reducing the stiffness of respective elements and potentially amending the load cases. The calculation will then readily give the new stress distribution or local RF's for the damaged structure and a $RF < 1$ could be interpreted as a structural failure. This method cannot make statements on damage creation, growth or failure mode but for an explicitly modeled damage it will estimate within acceptable computational effort the overall consequences better than any other non-FE approach (Figure 2).

3.0 A COMBINED APPROACH

On behalf of the German Forces procurement agency BWB, IABG develops and operates the German national standard software for assessment of weapon effectiveness and target vulnerability – UniVeMo (Universelles Verwundbarkeitsmodell). IABG also has access to several US codes, has experience with the Swedish software AVAL and participated in AVT-127 on “Comparison of Air and Land Vulnerability/Lethality Assessment Tools”. Based on this overview of software concepts, we are currently extending UniVeMo's capabilities by integrating third party software. In order to enable this in an efficient way a new simulation kernel was implemented providing well-defined C++ interfaces and offering integrated Lua 5 scripting. This fully modular approach enables us to integrate new modules while keeping their source code unclassified and open to cooperation.

We are looking for a method that predicts the overall consequences of arbitrary damage correctly in principle, while being handy enough to be integrated in classic vulnerability codes and efficient enough to comply with typical requirements concerning the duration of a vulnerability analysis. Unfortunately, none of the methods described above is alone able to satisfy the requirements of stochastic vulnerability analysis, whether they are inaccurate, need too much effort while delivering an unclear benefit or they simply take too much time. Consequently, a combination of methods needs to be established that composes the benefits of its constituents into an efficient ensemble.

In order to break down the complexity of a larger assembly's assessment down to a level that is more appropriate to be handled by most of the discussed methods, the core of a combined approach should be a linear implicit global finite element model. Setting up such a GFEM is not an easy task but fortunately these models are necessary for development of an aircraft and are available from the concept phase on. At the end of the development phase they are mature and validated against a major airframe static or fatigue test (MAST/MAFT). Due to the nature of aircraft design the elements are mostly flat shell elements. In order to transfer information from the vulnerability model to the GFEM, both have to be compatible on the level of components/elements. Ideally, the geometry and component breakdown of the target structure in the vulnerability model would be directly taken from the GFEM. Then the hit of a structural component in the vulnerability code can be directly assigned to an element in the FE model (Figure 15).

The level of damage suffered by a structural component – corresponding to a reduction in stiffness of the respective finite element – may be handled in the classic way: Depending on the primary and secondary threat effects (blast, penetration, hydraulic ram in tank structures etc.) damage is accumulated resulting in a kill probability $P_{k/h}$ of the multiply hit component or single hit kill probabilities are combined using the Survivor Rule (with the necessary attention). Based on the resulting $P_{k/h}$, a random decision can be taken if the component completely fails or not – or, if the underlying kill criterion was chosen respectively, $1 - P_{k/h}$ could be directly transferred as a stiffness reduction factor to the GFEM. At the end of all threat interactions in a single simulation loop the GFEM has accumulated all damage by stiffness reductions in the respective elements. On basis of a given set of load cases the new stress distribution and local RF's can be calculated as well as other global values that can be input to global kill criteria for structural integrity,

e.g. wing tip displacement (Figure 2: middle → ok, right → kill).

The details how the local damage and respective stiffness reduction can be calculated from the impact parameters depend on the structural component under investigation. In principle the complete set of methods described above is again applicable. However, at this stage we have broken down the original problem already by one order of magnitude. The finite elements for which we have to set a stiffness reduction have been already simplified to represent flat plates. Therefore read-across from other data is easier and empiric or engineering handbook methods can now be applied with more confidence.

At the other end, going from a classic fault tree (or even simpler assessments) to a Bayesian Network will not compromise existing models of system logic but will extend the possibilities, e.g. by providing the probability of structural integrity loss as a function of g-loading instead of a binary kill/survive statement for a given loading condition. This would make vulnerability results also more attractive to higher level simulations as they could decide to take out the aircraft from the scenario based on the maneuver during hit or could go on with a reduced flight envelope assuming that the pilot (or autonomous system) is aware of the damage.

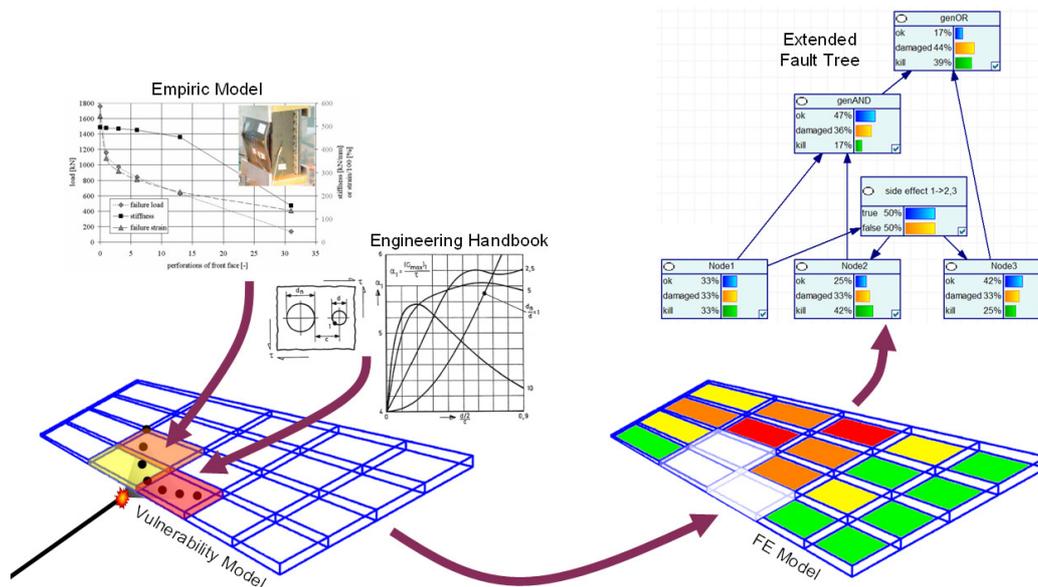


Figure 15: Combined approach for assessment of structural integrity

However, the aforementioned approach is at its very beginning. It needs to be written down in a more detailed concept paper and needs to be explored in some prototypic applications before starting specification and implementation of respective software modules.

4.0 SUMMARY AND CONCLUSION

Structural integrity is even more important for survivability of aircraft than for other platforms, because it must support all other primary factors, i.e. lift, thrust and control. Aircraft structure differs significantly from other systems as the level of redundancy depends on the actual loading and damage distribution. This makes structural integrity difficult to assess in classic vulnerability codes that calculate kill probabilities on component level and use fault trees to assess the overall consequences.

Several methods for assessing structural integrity have been briefly discussed, ranging from ignoring the

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problem, via mapping of empiric rules into a fault tree to most advanced finite element methods requiring super-computing capabilities. None of these methods is alone able to satisfy the requirements of stochastic vulnerability analysis, whether they are inaccurate, need too much effort while delivering an unclear benefit or they simply take too much time.

Consequently, a combination of methods was proposed based on a linear elastic finite element model of the complete aircraft structure, like it is used for aircraft development. This validated method allows breaking down the problem of structural integrity into a smaller order of magnitude, i.e. the order of flat plates for which many of the described methods can be applied with higher confidence. At the other end Bayesian Networks may help to expand today's binary kill/survival statements to more distinguished results.

A capability in vulnerability simulation taking realistically into account structural integrity would not only benefit the concept and definition phases of future platforms but would also support – together with structural health monitoring – efficient battle damage recovery and autonomous operation of unmanned combat platforms.

IABG is open to respective cooperation and hopes that this paper can be the seed for a common international effort to tackle the problem of assessing in more detail the structural integrity in vulnerability simulations – especially for airborne targets.

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