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MAINTAINING A SUBTLE BALANCE BETWEEN CONSERVATIVE AND PRECISE SOLUTIONS IN THE AEROSPACE STATIC CONCESSION PROCESSES

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Abstract: *The Static Stress represents a main task of the aerospace concessions workflow that is used to address the impact of manufacturing non-conformities on local and global criteria. The process benefits from conservatism, being most of the times a fast way to prove that a non-conformal part can withstand damage. Even so, critically loaded components are already subject to conservative assumptions that are applied in the certification stage. As a consequence, the results achieved are unrealistic, lowering the amount of conservatism demanding for extra time and economic resources. To cope with these aspects, an approach is proposed involving the use of parametric finite element method models for studying the variation of mechanical stresses due to possible non-conformity thresholds. Knock Down Factor charts are developed based on the effect of load redistribution. The approach can successfully be re-used for similar types of non-conformities. The given concepts are proved by means of practical examples throughout the work.*

Key words: *aerospace, concessions, DFEM, GFEM, Patran, SAMCEF.*

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1. INTRODUCTION

In the past decades, air transportation has emerged as the backbone of the international economy, having an annual growth rate of 5.9% and reaching a revenue of 754 billion U.S. dollars in 2017 [1]. Major aerospace manufacturers have focused on integrating innovation at all the life cycle stages of an aircraft to satisfy both the exigencies of the certification programs as well as mass market demands [2]. As an effort to lower the noise levels whilst extending the operational range of jet airliners, new design strategies have emerged, leading to the integration of alternative materials, complex shaped parts and lightweight structures as part of engine and airframe assemblies [3]. The recent trends in the field have significantly increased the manufacturing complexity and costs of components found in commercial aircrafts. Due to this fact, non-conformities (NC) are common and occur as the result of manufacturing or in service incidents [4]. To cope with such issues, the industry demanded for concession processes as a fast way to evaluate non-conformal parts, identify the impact that NC have on the aircraft's life cycle and propose adequate repair solutions. Existing concession approaches combine virtual prototyping based Non-Destructive Test procedures (NDT), CAD / CAE technologies and technical documentation research and methodologies [5, 6, 7]. The aim of the process is to identify all out of tolerance features, evaluate the impact of the NC, identify the baseline technical data that is subjected to change and justify that the non-conformal part can withstand damage with or without an imposed repair solution. While concessions proved to be highly efficient in supporting the jet airliner manufacturing processes, peculiarities arise due to the existence of already conservative assumptions found in the certification process that limits the boundary of fidelity [8]. In such cases, the parts are either sent to scrap or times consuming engineering judgment approaches are deployed. The present paper focuses solely on static stress, as a main task of the concessions workflow. Critically loaded parts that have a Reserve Factor (RF) close to one are studied by means of parametric Detailed Finite Element Models (DFEM) based on imposed displacements extracted from the Global Finite Element Model (GFEM). The aim of the study is to develop Knock Down Factor (KDF) charts by considering the ratio between baseline and concession case stress criteria that can be used with all types of local analysis (such as junction or local buckling). In this way, a subtle balance is achieved between conservative and precise solutions that lower the amount of parts that are sent to scrap while enhancing the overall manufacturing process. The work is divided in four parts: The first part of the work describes the concession process with emphasize on static stress criteria. In the second part, the principles of conservative assumptions are discussed and how applying them in both certification and concessions processes can lead to results that are not realistic. The third part of the work describes the proposed approach. To prove the given concepts, a study regarding a critical stiffener found in a Pylon Rear Mount Frame (RMF) tension fitting structure is presented by the end of the work.

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2. THE STATIC STRESS CONCESSION PROCESS

Concessions are a constitutive part of support activities that are deployed early in the jet airliners manufacturing life cycle. The aim of the process is to use NDT to evaluate the quality of parts by comparing coordinates of points with ideal references belonging to 3D CAD models (Fig. 1).

For all out of tolerance features, a design assessment is performed to identify the assembly impact that the NC pose. By using specific standards, guidelines and manufacturer procedures, repair or adjustment solutions are submitted for scrutiny. Any operational aircraft has passed certification to prove airworthiness. By the end of this process, technical documentation is generated to synthetize the criteria analyzed and the results achieved.

The static stress assessment represents an essential task in the concession process that consists of several sub-tasks (such as fatigue and damage tolerance assessment), being used to validate a repair solution by applying conservative assumptions to the impacted baseline criteria presented in the technical documentation. For example, a loss of section in a stiffened panel occurring due to a casting process non-conformity lowers the strength of the part, considering the increase of the mechanical stresses (Fig. 2).

Two approaches can be applied to study the impact of the NC:

- **The simplified method** represents the most widespread approach that is based on the geometric ratio method. It is used to approximate the impacted

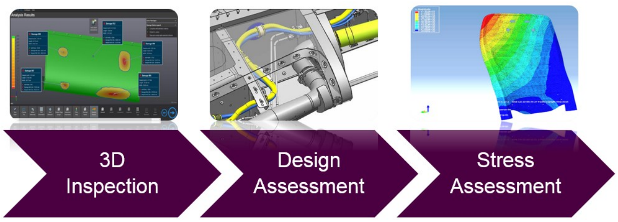
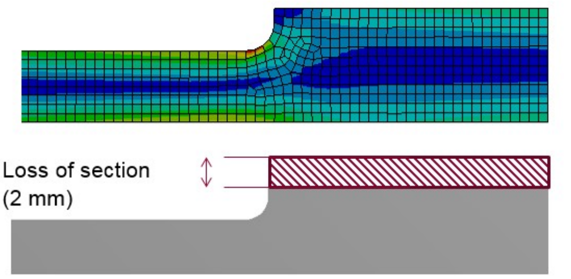


Fig. 1. A general concession process workflow.



Criteria	Baseline Stress (MPa)
X Component of Stress	22.16
Y Component of Stress	7.28
XY Component of Stress	1.67
Max Principal	23.93
Min Principal	-16.62
Equivalent Von Misses	22.62

Fig. 2. Study of a section loss in a stiffened panel.

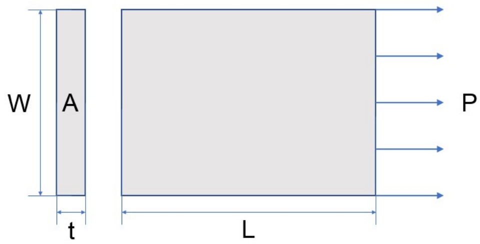


Fig. 3. Study of a section loss in a stiffened panel.

section with a simple plate subjected to in-plane loading (Fig. 3).

In this case, manufacturing issues (i.e. cracks, pores, loss of thickness, tool impacts) can be studied by considering that the thickness *t*, width *W* or length of the plate *L* differs from the nominal configuration. Knowing that the normal stress is a function of the applied load *P* and the area of the surface normal to the applied load *A*:

$$\sigma_{\max} = \frac{P}{A} . \quad (1)$$

The increase of the stress can be calculated by determining a KDF based on the geometric ratio between the baseline and the non-conformal surface area:

$$KDF = \frac{A_{baseline}}{A_{non-conformal}} > 1 . \quad (2)$$

The increase of the stress causes the reserve factor to decrease:

$$RF_{concession} = \frac{\sigma_{allowable}}{\sigma_{\max} \cdot KDF} . \quad (3)$$

Considering that the maximum stress in the structure is 23.93 MPa (Fig. 2) for the Max Principal Criteria and the Allowable Tensile Ultimate Stress *Ftu* for the material that the part is made of is 60 MPa, the baseline RF can be calculated as:

$$RF = \frac{\sigma_{allowable}}{\sigma_{\max}} = \frac{60MPa}{23.93MPa} = 2.50 \quad (4)$$

Knowing that the initial section was 1542 mm^2 and the section loss was of 149 mm^2, the new RF considering the non-conformity can be calculated as:

$$RF = RF_{baseline} \cdot \frac{A_{i-concession}}{A_{i-baseline}} = 2.26 . \quad (5)$$

- **The detailed method** represents an approach based on numerical solutions, usually derived from GFEM / DFEM calculations. In this case, NC are modeled by modifying baseline simulations or by developing them from scratch. For the example provided above, the new RF is calculated as the new maximum stress, divided by the allowable stress (Fig. 4):

$$RF = \frac{\sigma_{allowable}}{\sigma_{\max FEM}} = \frac{60MPa}{25.26MPa} = 2.37 . \quad (6)$$

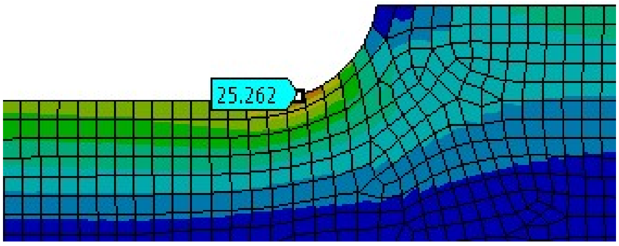


Fig. 4. Maximum stresses calculated by means of FEM calculations.

The detailed method is less conservative then the simplified one, being usually deployed when baseline RFs are close to one.

By the end of the static stress task, three decisions can be taken:

- **Acceptable as is**: the NC does not have any impact on the assembly conditions and all the RFs corresponding to the local and global criteria are greater than one.
- **Acceptable with further work performed**: the NC require a repair solution that is validated by both design and static stress assessment
- **Not acceptable**: the NC cannot be validated by design and / or stress assessment. In this case, the impacted components are sent to scrap.

3. CONSERVATIVE ASSUMPTIONS

Conservatism in airframe design involves lowering the amount of detail found in geometric data and calculation approaches, such that the modelled structures are less stiff than in practice. The principles of conservatism are the results of the past decades of structural design processes being embodied in most of the certification technical documentation. In this way, the time spent for developing or modifying airframe structures is lowered while the results achieved guarantee that the components can withstand damage. Four main type of conservatism can be distinguished:

- **Geometric conservatism:** only the most critical geometric parameter is considered when performing an analysis. For example, in a variable thickness spar, only the minimum thickness is used for calculating bearing behavior.
- **Material conservatism:** all materials have temperature dependent characteristics, being a common approach to consider the mechanical properties of a component at the most critical temperature that occurs in the area were the part is installed.
- **Load conservatism:** several load cases (LC) are used when performing the certification calculations. Load combination and correction factors are applied to eliminate uncertainties. Even tough, not all cases are physical.
- **GFEM conservatism:** the accuracy of FEM calculations is directly proportional to the density and quality of the mesh. Due to the big model sizes of GFEM models, coarse mesh settings are deployed. Therefore, the calculated stress gradients are steep.

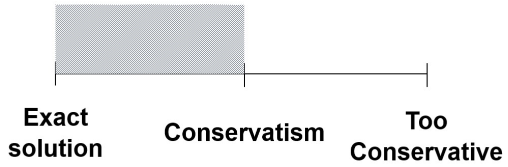


Fig. 5. Results achieved in airframe sizing processes.

From this point of view, the results achieved from the airframe sizing process are found at the half way between exact and conservative solutions interval (Fig. 5).

On the other hand, conservatism is also applied in the concession processes. Considering the components that are subject to high stresses, the sum of conservative assumptions applied can lead to $RF < 1$, resulting in the part being not acceptable (Fig. 6).

An example of conservative asumptions is performed for a RMF structure that is subjected to highly concentrated tensile loads (Fig. 7).

Calculations are performed by approximating the geometry with a channel fitting. The analytical solution is based on C.Y. Nyu methodology [9], the aim of the calculations being that of determining the RF for fitting wall bending, fitting end bending and shear through bolt hole.

The fitting wall tension is calculated as:

$$f_{ta} = \frac{P}{A}, \tag{6}$$

where P represents the applied ultimate tension load (N) and A – section area (mm^2).

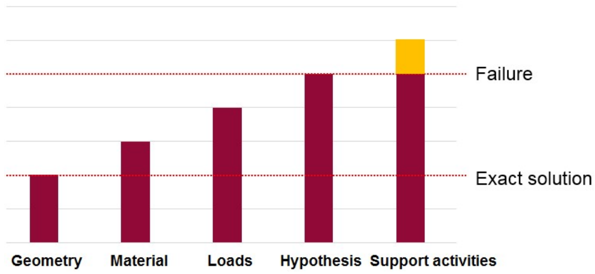


Fig. 6. Failure in concessions due to excessive conservatism.

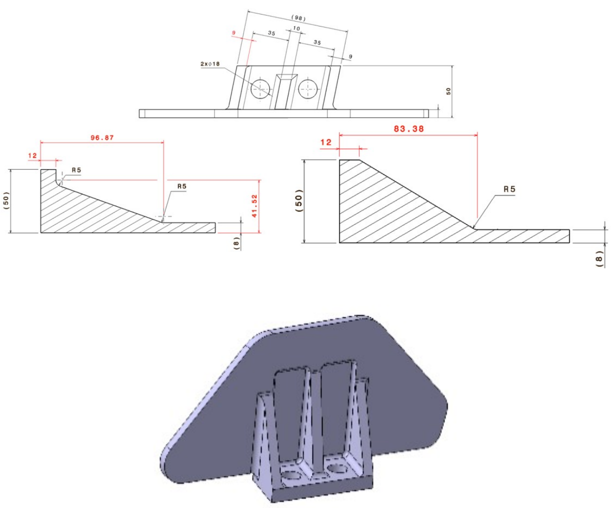


Fig. 7. Geometric measurements of the RMF tension fitting.

The fitting wall bending reserve factor is calculated as:

$$RF = \frac{F_{tu}}{\lambda f_{tu}}, \tag{7}$$

where F_{tu} is ultimate allowable tensile stress (MPa), λ – an applied fitting factor, and f_{tu} – the maximum tension stress on the fitting walls (MPa).

The fitting end bending reserve factor can be calculated as:

$$RF = \frac{F_{bu}}{\lambda f_{bu}}, \tag{8}$$

where F_{bu} represents the ultimate allowable bending stress (MPa) and f_{bu} – maximum bending stress on the fitting walls (MPa).

The Shear through bolt hole reserve factor can be calculated as:

$$RF = \frac{F_{su}}{\lambda f_{su}}, \tag{9}$$

where F_{su} represents the ultimate allowable shear stress (MPa) and f_{su} – maximum shear stress on the fitting walls (MPa).

The material used is Ti 6Al-4V (Grade 5) titanium alloy.

The following conservative assumptions are applied:

- Only the most critical geometric values of the two channel fitting profiles are considered (as described in Fig. 6). The effect of geometric stiffening (such as variable thickness or chamfers) is neglected.
- The limit load applied is multiplied by a load factor of 1.5.
- Allowable stresses are determined for the maximum temperature that occurs in the area where the part is installed.

The results achieved are summarized in Table 1.

To lower the amount of conservatism, a numerical study can be performed by using a detailed 3D DFEM. MSC Patran is used for Pre-and Post-Processing while solving the model is performed by LMS SAMCEF ASEF module (Fig. 8).

Table 1

Channel fitting calculations results

RF Fitting end bending	RF Fitting wall bending	RF Shear through bolt hole
1.75	2.92	1.07

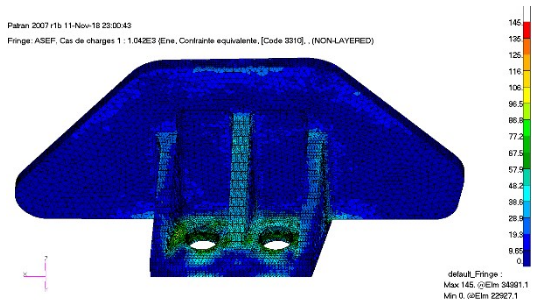


Fig. 8. Plot of the unaveraged Von Mises Stress Criteria.

Table 2

Channel fitting calculations results (based on DFEM)

RF Fitting end bending	RF Fitting wall bending	RF Shear through bolt hole
1.98	3.54	1.16

Nodal extractions are performed to estimate the fitting wall stresses. The results are shown in Table 2.

While the DFEM approach demands a high amount of time and resources, the results achieved take into account the loss of strength caused by the conservative assumptions applied.

4. PROPOSED APPROACH

For the RMF structure presented in the chapter above, a 0.8 mm section loss concession is presented for one of the stiffeners. Considering that the non-conformity does not cause any assembly issues, a study will be performed for evaluating the stress criteria (Fig. 9).

Based on the simplified approach, a section loss ratio can be applied to the stress *RF*. In this case, the most critical value occurs for the Max Principal Stress Criteria.

$$\sigma_{\max} = \sigma_{Max\,Pr.} = 344 MPa\ . \tag{10}$$

With an *Ftu* of 350 MPa, the stress reserve factor (RF_{stress}) can be calculated as:

$$RF_{Stress} = \frac{350 MPa}{340 MPa} = 1.02\ . \tag{11}$$

Knowing that the initial section area in the proximity of the stiffener is 1087 mm^2 and that the section loss is 43 mm^2, the new RF can be calculated as:

$$RF_{Stress} = 1.02 \cdot KDF = 1.02 \cdot 0.96 = 0.98\ . \tag{12}$$

The resulting RF has a value lower than one, therefore the solution is not acceptable.

Even so, the approach provides a coarse description of the stress redistribution due to the non-conformity, considering that the studied profile is stiffened by geometric features. In such cases, the increase of stress is not proportional to the loss of section considering that peak values occur in the proximity of the areas with steep geometric variation, such as rounded corners. Figure 10 presents the distribution of the stress tensor on a simple and chamfered plate. Considering a blend out non-conformity, the peak stress values migrate from the lower to the upper corner, the localized effect of the non-conformity being negligible.

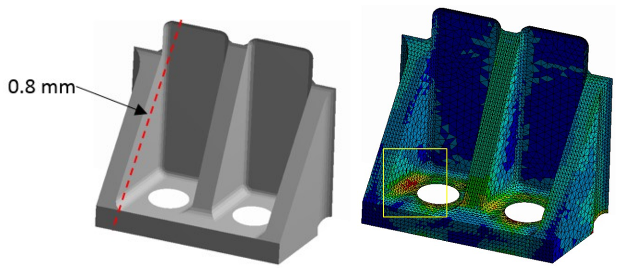
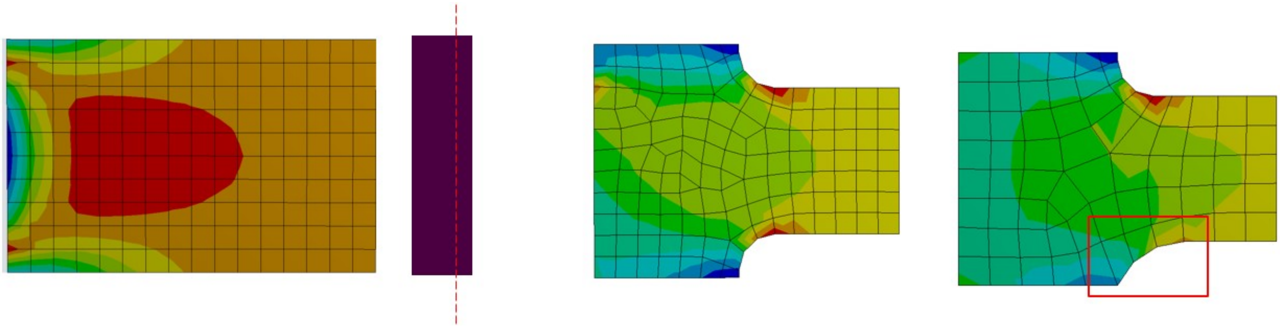


Fig. 9. Section loss non-conformity occurring in the channel fitting stiffener.



a b

Fig. 10. Plot of the normal stresses considering NC: *a* – simple plate (stress gradient constant with NC); *b* – Filleted plate.

From this point of view, stresses can provide a valuable insight on how NC impact the mechanical behavior of parts. Therefore, a less conservative *KDF* can be determined by performing a ratio between the baseline and the concession case stress calculated by using DFEM models.

$$KDF = \min\left(\frac{\sigma_{\max local_i}}{\sigma_{\max local_{i+1}}};\frac{\sigma_{\max global_i}}{\sigma_{\max 1global_{i+1}}}\right), \quad (13)$$

where: $\sigma_{\max\ i}$ – local or global stress tensor occulting due to NC; $\sigma_{\max\ i+1}$ – maximum baseline stress tensor occurring either adjacent to the non-conformity (local) or on the whole part (global).

A parametric study is developed by means of a DFEM model based on 3D meshing. Displacements are transferred as nodal constraints. For each LC used in the study a ratio is performed between the baseline and modified stresses (principal stresses, max principal, min principal, max shear, Von Mises) by translating the group of nodes corresponding to the stiffener's outer skin elements to recreate the non-conformity. A minimum and maximum offset range and result interval are considered.

Table 2 depicts the *KDF* values for local and global stress tensor for a non-conformity threshold value between 0.1 and 1.5 mm.

Table 2 KDF values

Local and global stress tensors

RFange	KDF Value Local	KDF Value Global
0.1 – 0.5	0.99	0.99
0.5 – 1.00	**0.99**	**0.99**
1.00 – 1.50	0.98	0.99

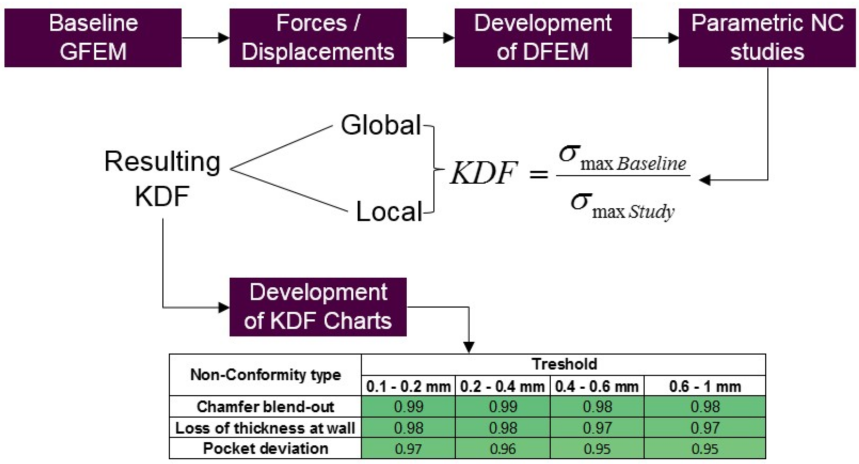
The new RF_{stress} can be calculated by applying the minimum *KDF* from Fig. 11:

$$RF_{Stress} = 1.02 \cdot KDF = 1.02 \cdot 0.99 = 1.00\,. \quad (14)$$

The result can be considered acceptable, if a warning is issued in the service repair manual of the aircraft.

It is important to highlight the fact that the DFEM models capture the mechanical behavior of a part in a greater depth than conservative models. It is therefore expected to achieve lower stresses than the one calculated in the baseline and thus higher RF margins. Even tough, the aim of the approach is to keep in mind the aspects of traceability and to provide a comprehensive method of assisting the concession process with respect to the philosophies involved.

To summarize the given concepts, Fig. 11 depicts the workflow of the proposed approach.



Non-Conformity type	Treshold			
	0.1 - 0.2 mm	0.2 - 0.4 mm	0.4 - 0.6 mm	0.6 - 1 mm
Chamfer blend-out	0.99	0.99	0.98	0.98
Loss of thickness at wall	0.98	0.98	0.97	0.97
Pocket deviation	0.97	0.96	0.95	0.95

Fig. 11. Workflow of the proposed approach.

7. CONCLUSIONS

The present paper addresses the peculiarities that occur for critically loaded parts in the process of static stress concessions. The proposed approach is based on a parametric DFEM study, having displacements extracted from GFEM and applied to the boundary of the model. A KDF chart is developed based on the most critical ratio occurring between the stress tensors with and without NC. The study is performed considering a threshold value such that recurrent cases can be covered. While the approach involves the development of DFEM models, traceability and process philosophies are respected. Thus, the amount of conservatism is lowered resulting in a greater efficiency of the process. The given concepts are proved for a study involving a critical stiffener from a RMF structure.

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