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TABLE OF CONTENTS

1.0 INTRODUCTION 1
1.1 BACKGROUND AND DISCUSSION 1
1.2 TERMINOLOGY 1
1.3 LIMITATIONS 2
1.4 NOMENCLATURE 5
2.0 DENTS IN SOLID METALLIC SHEET STRUCTURE 7
2.1 GEOMETRICAL ASSESSMENT 7
2.1.1 Background and Assumptions 7
2.1.2 Dent Classification 8
2.1.3 Interaction Assessment 8
2.1.4 Deformation Check 10
2.2 STATIC ANALYSIS 14
2.2.1 Background and Assumptions 14
2.2.2 Linear Procedure (Shallow and Mild Dents) 14
2.2.3 Non-Linear Procedure 18
2.2.4 Open-Hole Procedure 22
2.3 STABILITY ANALYSIS 27
2.3.1 Background and Assumptions 27
2.3.2 Stability Analysis Procedure 29
2.4 FATIGUE ANALYSIS 32
2.4.1 Permanent Dents 32
2.4.2 Temporary Dents 33
2.5 ANALYSIS FOR RE-POSITIONING FLIGHTS (LIPSKIN ONLY) 34
2.5.1 Background and Assumptions 34
2.5.2 Re-Positioning Flight Analysis Procedure 34
3.0 APPENDIX A: HOLES INTERACTION 38
4.0 APPENDIX B: DENT IN LIPSKIN 40
5.0 APPENDIX C: LINEAR VS. NON-LINEAR BENDING STRESSES 43
6.0 REFERENCES 47

LIST OF FIGURES

Figure 1-1 Damage location for applicability of Dent Analysis method 2
Figure 1-2 Dent Analysis Flowchart 3
Figure 2-1 Definition of Geometric Parameters 7
Figure 2-2 Geometric Parameters in Case of Interaction of Two Dents 7
Figure 2-3 Dent Interaction Flowchart 10
Figure 2-4 Dent Radius Geometry 11
Figure 2-5 Typical Stress-Strain Curve (ESOM FB05-1) 11
Figure 2-6 Deformed Check Flowchart 13
Figure 2-7 Extract from Ref.[2], Figure D3.30 14
Figure 2-8 Linear Static Analysis Flowchart 17
Figure 2-9 Non-Linear Static Analysis Flowchart 21
Figure 2-10 Open Hole in Far Field 22
Figure 2-11 Cozzone Assumption on Non-Linear Bending Stress 23
Figure 2-12 Open Hole Static Analysis Flowchart 26
Figure 2-13 Panel Size for Global Buckling Analysis 28
Figure 2-14 Panel Size for Buckling Cut-Off Check 28
Figure 2-15 Stability Static Analysis Flowchart 31
Figure 2-16 Repositioning Flight Dent Geometry Variables 36
Figure 2-17 Re-Positioning Flight Analysis Flowchart 37
Figure 3-1 Equal diameter holes interaction (fatigue) 38
Figure 3-2 Infinite thin elements with a hole under tensile loads (Peterson) 38
Figure 3-3 Stress concentration factor 39
Figure 4-1 Shallow Dent in Lipskin (d<t/2) – Max Principal Stress 41
Figure 4-2 Mild Dent in Lipskin (d=t) – Max Principal Stress 41
Figure 4-3 Shallow Dent in Lipskin (d<t/2) – Hoop Stress 42
Figure 4-4 Mild Dent in Lipskin (d=t) – Hoop Stress 42

LIST OF TABLES

Table 2-1 Dent Classification Criteria 8

Table 3-1 Stress concentration factors calculation 39

The technical output from this process must be properly classified in accordance with EEP 1038 – Export Compliance. For any questions please contact your ITC Focal.

1.0 INTRODUCTION

1.1 BACKGROUND AND DISCUSSION

To improve airline customer experience, Aftermarket Technical Services (AMTS) is always working toward providing a better support to in-service product. Operators are increasingly requesting less than a 4-hour AOG (Airplane On Ground) response, consistent "fly-on" dispositions, and most importantly, no grounding of aircraft due to minor impact damage.

AMTS is addressing this challenge by standardizing the assumptions and methods used in the structural analysis and disposition of dents "use as-is" in pristine structure. The sources of variation in the analysis are attributed to the following:

- Derivation of the stress concentration factor for interaction effects between dents, panel edges, and other damages
- Inconsistent use of linear vs non-linear material properties and loading assumptions
- Determination of the maximum permissible fatigue life
- Different applications of the "open-hole" method
- Inconsistent boundary conditions applied for stability analysis

AMTS is eliminating these variances by defining a standardized dent analysis procedure. The method is the result of a process improvement Kaizen event and years of engineering experience and observations.

The analysis begins with a geometrical assessment of the damage. The assessment yields a standard classification of dents that determines the analysis approach and assumptions. The static analysis sees a linear and non-linear approach plus an open hole approach. The analysis methods are ordered by conservatism and are analyzed in series to mitigate negative static margins of safety. Once a positive static margin of safety is obtained, a stability and fatigue analysis are performed. The dent classification, as well as which static check yielded positive margins, determines the stress concentration factor applied in the fatigue analysis.

Figure 1-2 summarizes the dent analysis described in this ESOM.

Note: this is a structural ESOM only. This ESOM does not consider Aerodynamic or Thermal issues. For long term fly-ons, the thermal analysis group must be consulted for dents in lipskin areas. The aerodynamic group must be consulted for all fly-ons as well as for permanent dents. Previous approvals from SME's are acceptable.

1.2 TERMINOLOGY

The following terminology is used within this ESOM, which is common to the Aftermarket organization.

Fly-on: when an aircraft is allowed to fly with an unrepaired damage (in this case, a dent in the lipskin). Usually, fly-ons have a short life limit, for example, 1 or 2 FC (flight cycles) or 10 days. Usually 1 or 2 FCs allow the airline to reposition the aircraft and return to base to perform a repair.

Repositioning Flight Analysis: the analysis containing the minimum checks required to allow an aircraft to fly-on for a short duration of 2 FC during which the Airline "repositions" the aircraft from the current location to another location, usually, their base where they can repair the damage. The Repositioning Flight Analysis guarantees that the airworthiness and regulation requirements for the damaged component are still met and it is safe to fly with the unrepaired damage.

Rejection: when the request of fly-on from a Customer (airline or the organization in charge of performing the repair for them) cannot be accepted, the case is deemed to be rejected. This means the aircraft cannot fly with the damage in an “as-is” condition (unrepaired).

1.3 LIMITATIONS

The Static Analysis, Stability Analysis, and Fatigue Analysis in Sections 2.2, 2.3, 2.4 respectively are applicable for dents 1.5” from a line of fasteners, as shown in Figure 1-1.

Note: When the edge of a dent is within the 1.5” from a line of fasteners, the Kt may be higher due to the dent and fastener hole interaction. Contact AMTS SME for proper analysis assumptions.

Note: For damages to a Lipskin that are within 1.5” from the forward bulkhead or splice fasteners, perform the Deformation Check described in Section 2.1.4 and then use the Re-Position Flight Analysis in Section 2.5.

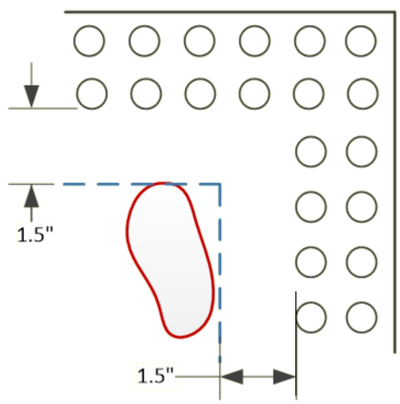

Figure 1-1 Damage location for applicability of Dent Analysis method

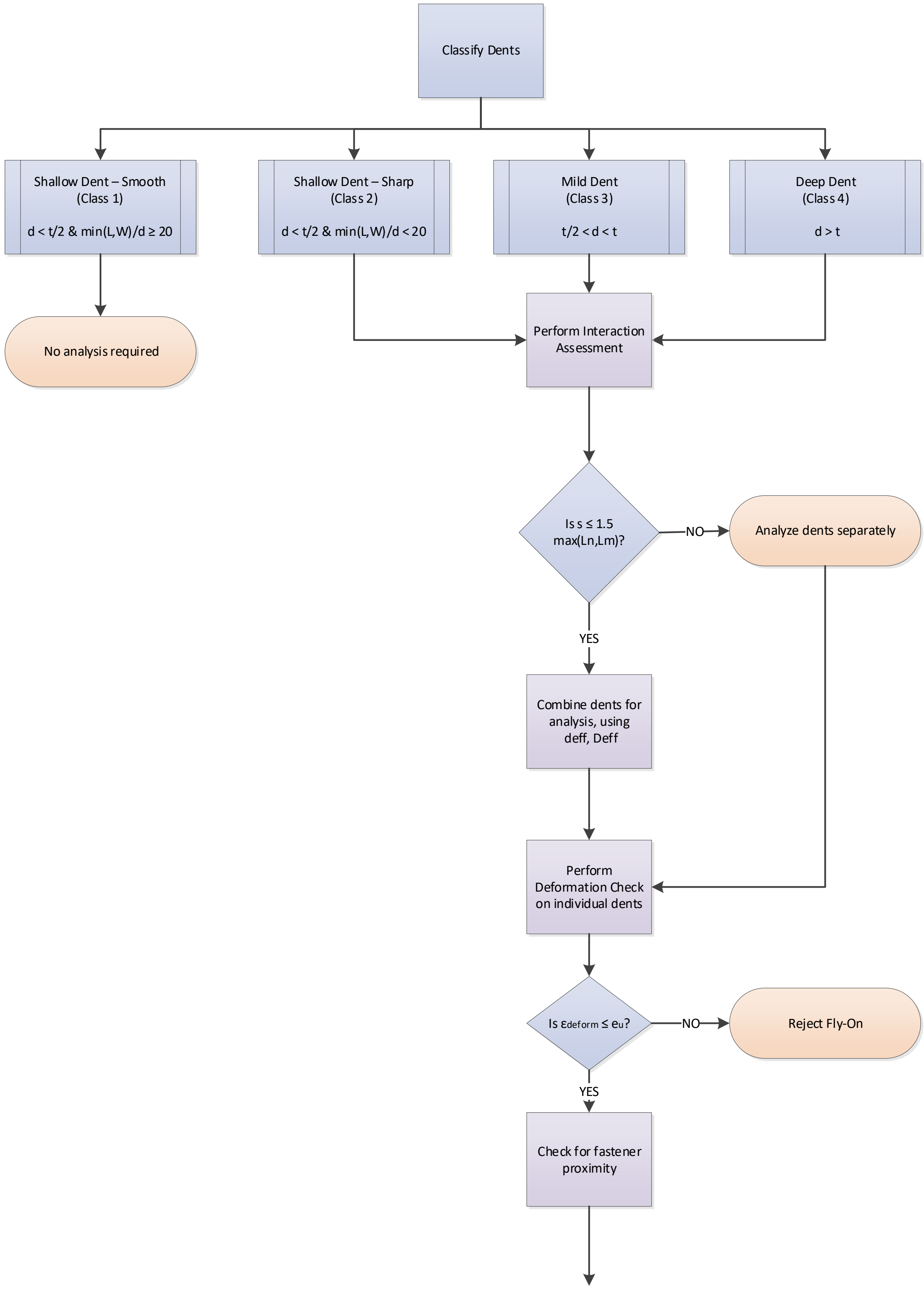

Figure 1-2 Dent Analysis Flowchart

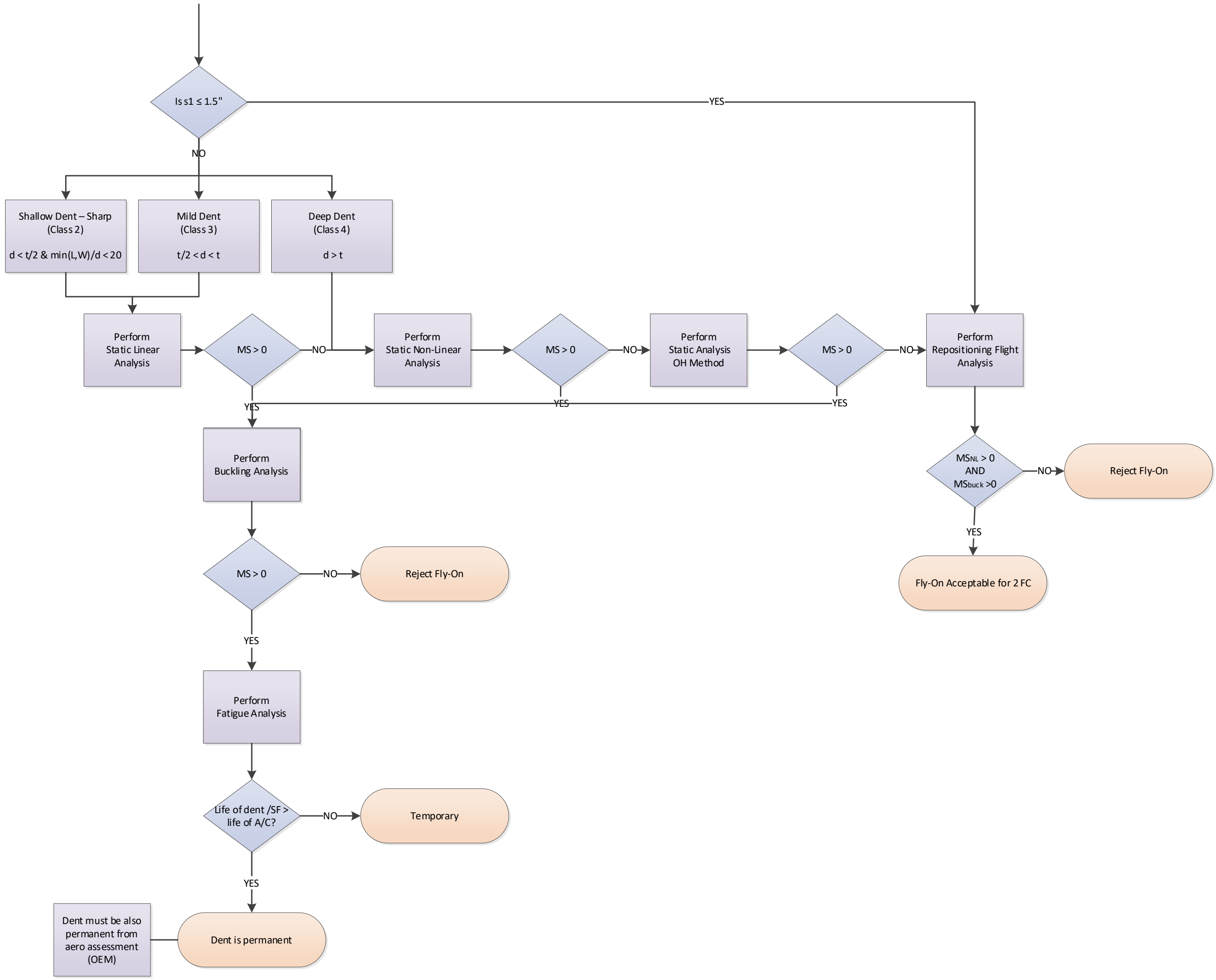

Figure 1-2 Dent Analysis Flow Chart – cont'd

1.4 NOMENCLATURE

Variable	Description	Units	Units
AR	Dent aspect ratio	-	
a_n, L_n, L_m	Major diameter of $dent_n$ or $dent_m$	in	
b_n, W_n, W_m	Minor diameter of $dent_n$ or $dent_m$	in	
b_{opt}	Optimized buckling size	in	
d, d_n, d_m	Depth of $dent_n$ or $dent_m$	in	
d_{eff}	Assumed effective dent depth for interacting dents	in	
d_{new}	Reduced depth of dent	in	
d_{opt}	Optimized dent depth	in	
D, D_n	Assumed dent diameter	in	
D_{eff}	Assumed effective dent diameter for interacting dents	in	
E	Modulus of elasticity	msi	
e_m	Distance between edge of dent and edge of fastener hole	in	
ε_{deform}	Deformed strain	% in/in	
$\varepsilon_{deform,new}$	Reduced deformed strain	% in/in	
ε_{ult}	Ultimate Strain	% in/in	
FC	Flight cycles		
Ftu	B-Basis Ultimate tensile allowable at room temperature	ksi	
Ftu_{ult_strain}	Typical Ultimate Tensile Allowable at Ultimate Strain level at room temperature	ksi	
Fcy	B-Basis Compression Yield Allowable at room temperature	ksi	
F_b	Plastic bending allowable	ksi	
$F_{cr,c}$	Elastic buckling allowable compression stress	ksi	
F_{allow}	Applied material allowable (for margin calculation)	ksi	

K_{net}	Net section stress concentration factor	-	
K_t	Fatigue stress concentration factor	-	
v	Poisson's ratio	-	
NSF	Net-section factor	-	
L_{curve}	Surface profile path length in short curvature direction	in	
M_{dent}	Offset bending moment	In-Lbf/in	
N_{eff}	Effective in-plane running load	Lbf/in	
OH	Open Hole		
R	Fatigue Stress Ratio (min/max)	-	
r	Dent radius of curvature	in	
SF	Scatter Factor	-	
s	Distance between interacting dents, edge to edge	in	
s_1	Distance between edge of dent and edge of fastener hole	in	
σ_L	Linear stress	ksi	
σ_{NL}	Non-linear stress	ksi	
$\sigma_{MAX,Pr}$	Maximum principal stress	ksi	
$\sigma_{min,Pr}$	Minimum principal stress	ksi	
σ_{MAX}	Maximum in-plane stress	ksi	
σ_{buck}	Buckling stress	ksi	
$\sigma_{equivalent}$	Equivalent uniform in-plane stress (Cozzone assumption)	ksi	
σ_{OH}	Open-hole stress	ksi	
TRF	Temperature reduction factor	-	
t	Thickness of skin or face sheet	in	

2.0 DENTS IN SOLID METALLIC SHEET STRUCTURE

2.1 GEOMETRICAL ASSESSMENT

2.1.1 Background and Assumptions

The geometrical assessment is a combination of an interaction evaluation and a deformed strain check. The result of these two checks, along with the dent smoothness ratio and thickness of the sheet, determines the classification of the dent. Dents can be classified as: shallow smooth, shallow sharp, mild and deep. The dent classification determines the type of static analysis to be performed.

The geometrical quantities used within this ESOM are depicted in Figure 2-1 and in Figure 2-2.

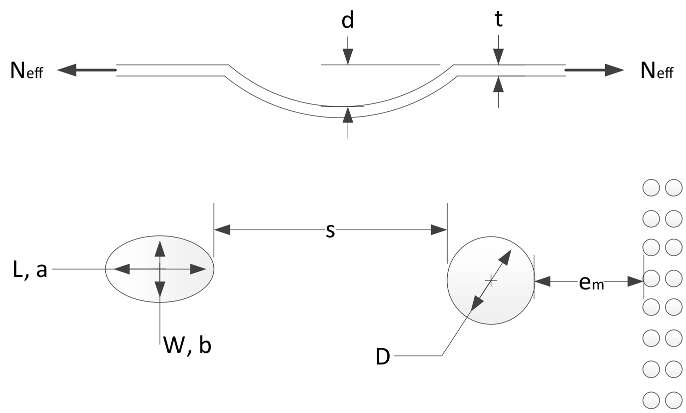

Figure 2-1 Definition of Geometric Parameters

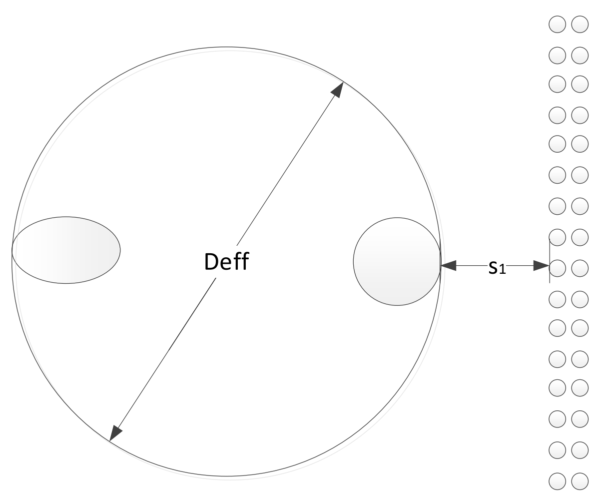

Figure 2-2 Geometric Parameters in Case of Interaction of Two Dents

2.1.2 Dent Classification

Dents can be classified into categories depending on their depth, d_n, relative to the skin thickness, t. The static analysis performed in Section 2.2 is dependent on the Dent Classification.

Table 2-1 Dent Classification Criteria

DENT CLASSIFICATION	CRITERIA	ANALYSIS
Shallow Dent – Smooth (Class 1)	$d_n \leq \frac{t}{2}$ and $\frac{\min(L_n, W_n)}{d_n} \geq 20$	No analysis required
Shallow Dent – Sharp (Class 2)	$d_n < \frac{t}{2}$ and $\frac{\min(L_n, W_n)}{d_n} < 20$	Linear Analysis Section 2.2.2
Mild Dent (Class 3)	$\frac{t}{2} < d_n \leq t$	Linear and Non-linear Analysis Section 2.2.2 and 2.2.3
Deep Dent (Class 4)	$d_n > t$	Non-Linear Analysis Section 2.2.3

If Class 1, it is assumed the dent is shallow and does not significantly increase the bending stress. The skin can carry the pristine load and therefore no analysis is required.

If Class 2 or 3, proceed to Linear Static Analysis in Section 2.2.2.

If Class 4, the dent depth exceeds the skin thickness and it is assumed the dent behaves Non-Linearly. Proceed to Non-Linear Static Analysis in Section 2.2.3.

In case of dents interaction where both dents are Class 1, no analysis is required.

Note: If the dent is classified as Class 2 or 3 and fails the linear check, it may still be found acceptable by subsequently performing the non-linear check found in Section 2.2.3. Similarly, if a Class 4 dent fails the non-linear check, it may still be found acceptable after performing an open-hole check as described in Section 2.2.4.

2.1.3 Interaction Assessment

Stress interactions between dents should be considered in the presence of multiple dents or damages. APPENDIX A provides guidelines on when interaction effects are present dependent on dent spacing "s".

There will be interaction effects for damages that fall within 1.5D edge to edge (*s*), or 2.5D center Step 1 to center (*e*), from dent to another damage or geometry change, where D is the larger of the two damage dimensions.

If one of the dents is Class-1, no interaction is required.

2.1.3.1 Interaction Assessment Steps

Obtain geometrical dimensions for $dent_n$ and $dent_m$: major diameter of dent (L_n, L_m), minor diameter of dent (W_n, W_m), depth of dent (d_n, d_m).

Obtain edge to edge spacing, s, between $dent_n$ and $dent_m$.

Determine if the dents interact using Eqn. 2-2-1.

$$Interact = \begin{cases} \text{"Yes"}\ if\ s \leq 1.5 * \max(L_n, L_m) \\ \text{"No"}\ otherwise \end{cases}$$ **Eqn. 2-2-1**

Step 2

Step 3

If yes, there are interaction effects and the damages will need to be combined for analysis. Continue to Step 4.

If no, there are no interaction effects between dents and they may be analyzed separately. Proceed to Deformed Strain Check in Section 2.1.4.

If the dents interact, use the following assessment to determine the effective geometry of interacting dents. These assumptions envelop the worst case combined scenario.

Step 4

Note: assuming different geometries based on interaction can result in an unrealistic deformed strain. Using the max depth with the corresponding diameter will result in the highest deformed strain (sharp, L/d ratio relatively low). Assuming the largest diameter with the deepest dent will result in a lower deformed strain (shallow, L/d ratio relatively high).

For every check (Static Linear, Static Non-Linear, Static OH (Open Hole), Stability, Repositioning and Fatigue), the assumed effective depth, d_{eff}, for the interacting dents is determined from Eqn. 2-2-2.

$$d_{eff_{bending}} = \begin{cases} \text{avg}(d_n, d_m)\ if\ critical\ load\ case\ is\ tention \\ \max(d_n, d_m)\ if\ critical\ load\ case\ is\ compression \end{cases}$$ **Eqn. 2-2-2**

Note: for tensile loading, the average dent depth is assumed because the load straightens out and decreases the dent depth.

For the Static Check in Section 2.2.4 and Buckling Check in Section 2.3, the assumed effective diameter, D_{eff}, for the interacting dents is determined from Eqn. 2-2-3, where $D_n = \max(L_n, W_n)$ and $D_{n+1} = \max(L_{n+1}, W_{n+1})$.

$$D_{eff} = D_n + s + D_{n+1}$$ **Eqn. 2-2-3**

2.1.3.2 Interaction Assessment Flowchart

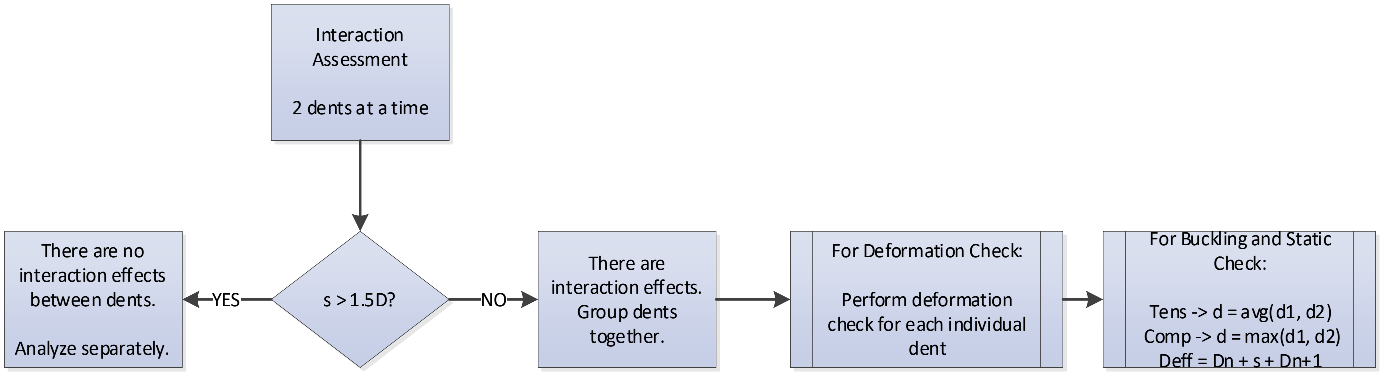

Figure 2-3 Dent Interaction Flowchart

2.1.4 Deformation Check

In case of multiple dents, perform the Deformation Check for each individual dent.

The deformed dent strain value is compared to the material ultimate total strain value. The results of this comparison will determine if the dented material remains within the allowable strain limits, making it acceptable to proceed with the next analysis.

For the Deformation Check, the one-time maximum strain allowable from the typical stress-strain curve in MMPDS (see Ref. [13]) is used.

For example, from the stress-strain curve of the Al 2219-T62, the typical ultimate total strain value is 6% - 7%. Ref. [8].

2.1.4.1 Deformation Check Steps

Step 1 Use dent geometry from Section 2.1.1 and 2.1.3.1

Step 2 Calculate the dent radius, r, based on geometry.

$$r = \frac{[(0.5 * max(L, W, D))^2 + d^2]}{2d}$$ **Eqn. 2-2-4**

Note: The maximum dimension L in case of ellipsoidal dent or D in case of circular dent provides the highest deformed strain.

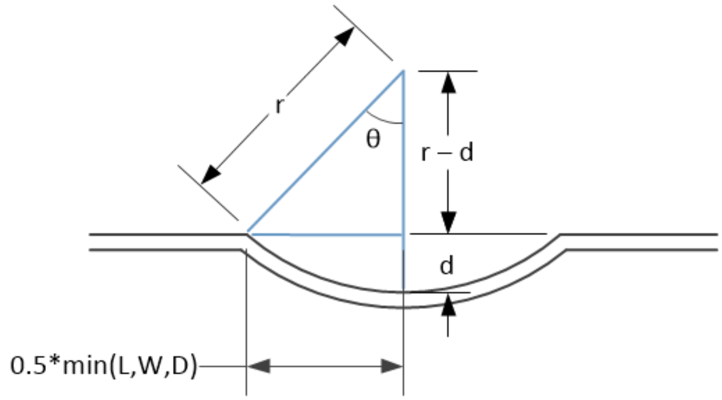

Figure 2-4 Dent Radius Geometry

Calculate the deformed strain, ε_{deform}.

Step 3

$$\varepsilon_{deform} = \frac{\Delta L}{L} = \frac{d}{(r-d)}$$ **Eqn. 2-2-5**

Eqn. 2-2-5 provides the total strain at the center of the dent, where the deformation value is higher. The formula is validated by FEM in Ref. [9. The lipskin model and impactor model used for validation can be found in Ref. [10] and [11] and the modeling is described in ESOM KD25-20 in Ref. [12].

Step 4

Use the typical material Stress – Strain curve from Ref. [13], (for example, Figure 3.2.17.1.3(b) for aluminum 2219-T62) to obtain the ultimate total strain, e_u corresponding to the ultimate tensile allowable, Ftu (see Figure 2-5 for definition of e_u and Ftu) and compare e_u to the "e" in Tabular allowable, B-Basis in Ref. [13], for the same material (for example, Table 3.2.17.0(b1), for aluminum 2219-T62). Take the minimum between e_u and "e" tabular.

For example, the ultimate total strain in both Ref. [13], Table 3.2.17.0(b1), for Collins lipskin thicknesses (0.040""-0.249") and Ref. [13], Figure 3.2.17.1.3(b) is 7%.

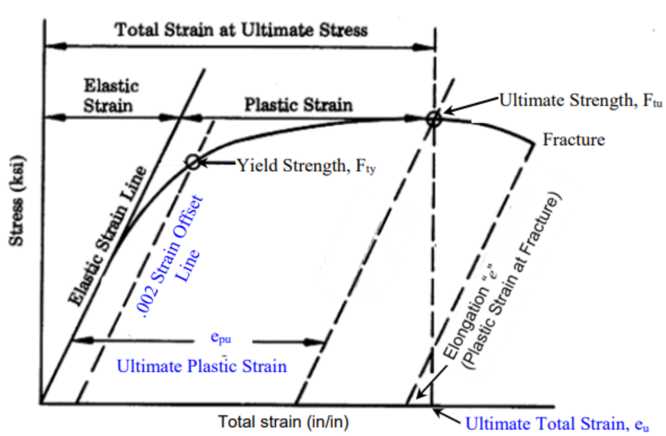

Figure 2-5 Typical Stress-Strain Curve (ESOM FB05-1)

Determine if the calculated deformed strain, ε_{deform}, is less than the ultimate total strain, ε_u.

$$Deformation\ Check = \begin{bmatrix} \text{"Pass"}\ if\ e_u > \varepsilon_{deform} \\ \text{"Fail"}\ otherwise \end{bmatrix}$$ **Eqn. 2-2-6**

Step 5 If “Pass”, proceed to fastener proximity check.

If the Deformation Check fails, reject the fly-on.

2.1.4.2 Deformation Check Flowchart

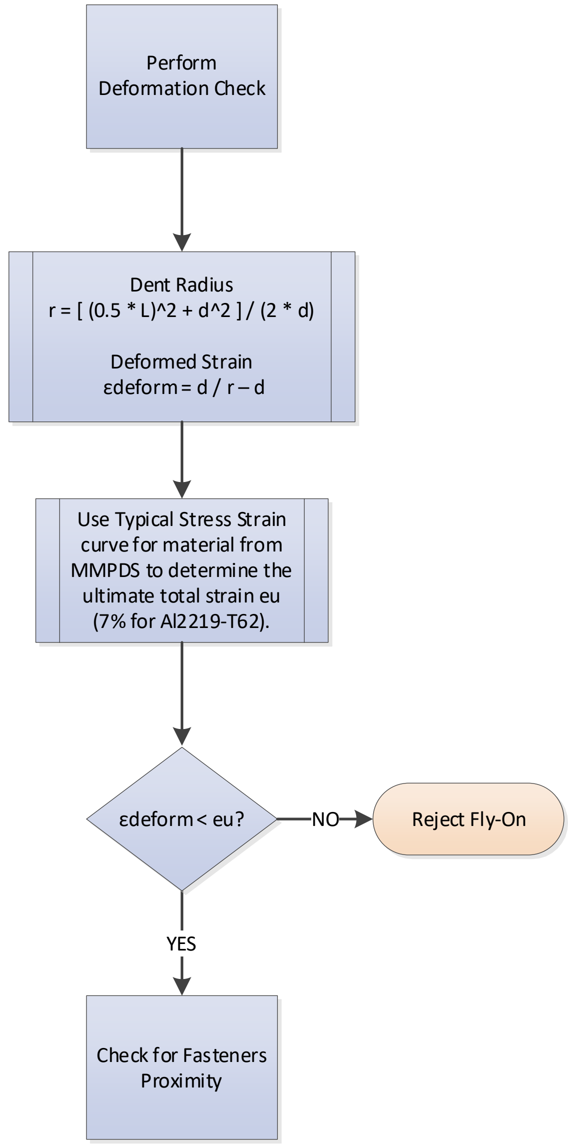

Figure 2-6 Deformed Check Flowchart

2.2 STATIC ANALYSIS

2.2.1 Background and Assumptions

The static analysis includes three methods: linear, non-linear, and open hole.

The methods are analyzed in series by decreasing order of conservatism. For example, if a dent demonstrates negative margins of safety for both a linear and non-linear analysis, dent damage may still be acceptable if it demonstrates positive margins for an open-hole check.

For linear and non-linear analysis, the skin carries in-plane loads and does not rely on redistribution. For open-hole, skin does not carry in-plane loads and the loads redistribute around the dent (acting like an open hole).

2.2.2 Linear Procedure (Shallow and Mild Dents)

The dent introduces an offset moment (see Figure 2-7) and creates a hard point at the edge of the dent, such that the severe hard point may lead to skin failure. Ref. [1], Ref. [2] and Ref. [3] provide guidelines on linear dent analysis.

The offset moment equation and the stress used together with it are correlated by finite element analysis of a dented lipskin. The correlation is shown in APPENDIX B.

Note: the "Linear" Analysis refers to linear loading but accounts for material non-linearity with the use of plastic bending.

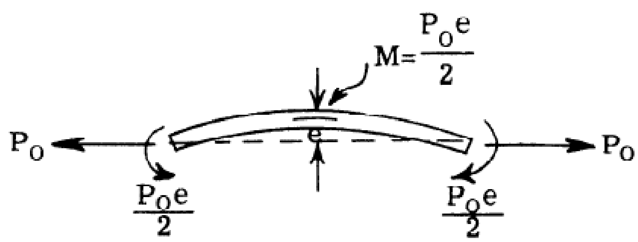

Figure 2-7 Extract from Ref.[2], Figure D3.30

2.2.2.1 Linear Analysis Steps

Use dent geometry from Section 2.1.1 and 2.1.3.1.

Step 1

Obtain the most critical maximum and minimum principal stress for the dented area. The down-selection should be conducted based on margin of safety, which should include the effects of temperature, since a condition with lower stresses may result more critical due to higher temperature, compared to another with a higher stress but lower temperature.

Step 2

Principal stresses can be found in the certification reports or can be calculated from running loads or stresses (in certification reports or extracted from Nastran f06 result file).

If $\sigma_{MAX,Pr} > 0 \; and \; \sigma_{min,Pr} < 0,$ repeat Step 3 through Step 7 with $\sigma_{MAX} = \sigma_{MAX,Pr}$ first (tension case) and then with $\sigma_{MAX} = |\sigma_{min,Pr}|$ (compression case).

If $\sigma_{MAX,Pr} \leq 0$, $\sigma_{MAX} = |\sigma_{min,Pr}|$ (compression case, no tension critical).

If $\sigma_{min,Pr} \geq 0$, $\sigma_{MAX} = \sigma_{MAX,Pr}$ (tension case, no compression critical).

Step 3

Calculate the effective running load as:

$$N_{eff} = \sigma_{MAX} * t \qquad \textbf{Eqn. 2-2-7}$$

Step 4

Calculate the dent offset moment using N_{eff}:

$$M_{dent} = \frac{N_{eff} * d}{2} \qquad \textbf{Eqn. 2-2-8}$$

Step 5

In case of dents interaction, d is the d_{eff} expressed by Eqn. 2-2-2 and max (L_n,W_n) = D_{eff} in Eqn. 2-2-3.

Calculate the linear bending stress, σ_L, due to the offset bending moment:

$$\sigma_L = \frac{6 * M_{dent}}{t^2} \qquad \textbf{Eqn. 2-2-9}$$

Step 6

Note that the in-plane stress is not combined with the bending stress because the dent bending stress is equivalent to a local peak stress (see APPENDIX B for more detail and FEM correlation).

Obtain the material allowable, F_{allow}.

$$F_{allow} = \begin{bmatrix} F_b = F_{tu} + f_o * (k-1) \approx 1.5 * F_{tu} \; if \; \sigma_{MAX} = \sigma_{MAX,Pr} \\ F_{cu} \; if \; \sigma_{MAX} = |\sigma_{min,Pr}| \end{bmatrix} \qquad \textbf{Eqn. 2-2-10}$$

where Ftu is the B-Basis allowable in Ref. [13], (for example, for aluminum 2219-T62, Table 3.2.17.0(b_1) gives a 55 ksi for B-Basis allowable).

Note: For the linear analysis, the plastic bending allowable, Fb, is to be used for tension loading (see ESOM FB05-5 in Ref. [2] and Ref. [4])

Calculate the Margin of Safety, MS_L.

$$MS_L = \frac{F_{allow} * TRF}{\sigma_L} - 1 \qquad \textbf{Eqn. 2-2-11}$$

Step 7

If MS_L is positive, proceed to Stability Analysis in Section 2.3.

If MS_L is negative, mitigate with the Non-Linear Analysis in Section 2.2.3.

2.2.2.2 Linear Analysis Flowchart

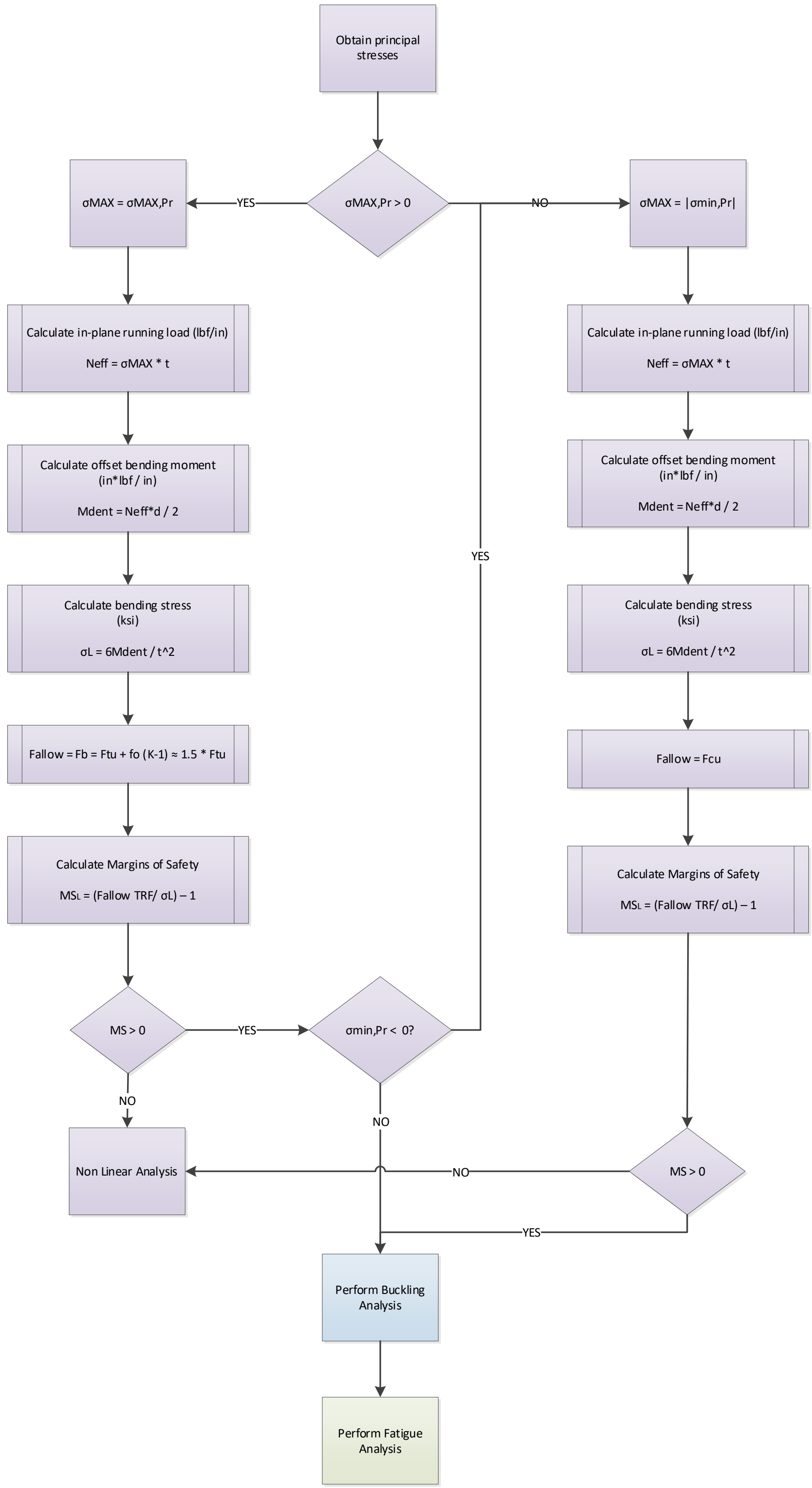

Figure 2-8 Linear Static Analysis Flowchart

2.2.3 Non-Linear Procedure

Roark's "Formulas for Stress and Strain," Ref. [5], provides a theoretical solution to the uniformly loaded rectangular plates with large deflections. Roark Table "Rectangular plates under uniform load producing large deflection" at page 452 of Ref. [5] provides a relation among load, deflection and stress tabulating numerical values of dimensionless coefficients qb^4/Et^4, $\sigma_d b^2/Et^2$ and $\sigma b^2/Et^2$ (where q is the applied pressure, σ_d is the diaphragm stress, σ is the total stress, E and t are the elastic modulus of the material and the thickness respectively), for various boundary constraints as well as aspect ratios of a/b (or L_n / W_n). For a fixed aspect ratio and known material, it is possible to calculate the bending stress as the difference from the total stress and the diaphragm stress. The lipskin application falls in the $0 < qb^4/Et^4 < 12.5$ range of this Roark Table.

For relatively thin plates with a large displacement (greater than one-half the thickness), the plate behaves as a membrane and can develop into non-linear characteristic behavior in order to account for the effects of the large deformation. The middle surface becomes appreciably strained and the stresses, called diaphragm stress, enables the plate to carry part of the load as a diaphragm in the in-plane direction. Therefore, the deformed dent still can carry in-plane loads, but the bending moment is reduced to account for the material in the deformed strain state.

This approach is applicable to mild and deep dents in Table 2-1.

A study found in APPENDIX C shows that the non-linear bending stress at the center of the plate is approximately 0.5 times the linear stress for an aspect ratio greater than 1.5 and 0.6 times the linear stress for an aspect ratio less than or equal to 1.5. See APPENDIX C for details.

2.2.3.1 Non-Linear Analysis Steps

Use dent geometry from Section 2.1.1 and 2.1.3.1.

Step 1 Obtain the most critical maximum and minimum principal stress for the dented area. The down-selection should be conducted based on margin of safety, which should include the effects of temperature, since a condition with lower stresses may result more critical due to higher temperature, compared to another with a higher stress but lower temperature.

Step 2 Principal stresses can be found in the certification reports or can be calculated from running loads or stresses (in certification reports or extracted from Nastran f06 result file).

If $\sigma_{MAX,Pr} > 0\ and\ \sigma_{min,Pr} < 0,$ repeat Step 3 through Step 7 with $\sigma_{MAX} = \sigma_{MAX,Pr}$ first (tension case) and then with $\sigma_{MAX} = |\sigma_{min,Pr}|$ (compression case).

If $\sigma_{MAX,Pr} \le 0$, $\sigma_{MAX} = |\sigma_{min,Pr}|$ (compression case, no tension critical).

If $\sigma_{min,Pr} \ge 0$, $\sigma_{MAX} = \sigma_{MAX,Pr}$ (tension case, no compression critical).

Step 3 Calculate the effective in-plane running load, $Neff$:

$$Neff = \sigma_{MAX} * t$$ **Eqn. 2-2-12**

Step 4 Calculate the offset bending moment, M_{dent}.

$$M_{dent} = \frac{N_{eff} * d}{2}$$ **Eqn. 2-2-13**

Step 5 In case of dents interaction, d is the d_{eff} expressed by Eqn. 2-2-2 and max (L_n,W_n) = D_{eff} in Eqn. 2-2-3.

Step 6 Determine the dent aspect ratio, AR. In case of dents interaction, AR = 1 (see APPENDIX C, page 44 for a/b=1.

$$AR = \frac{\max(L_n, W_n)}{\min(L_n, W_n)}$$ **Eqn. 2-2-14**

Calculate the non-linear bending stress, σ_{NL}, due to the dent offset bending moment, M_{dent}. The non-linear bending stress equations in Eqn. 2-2-15, are found comparing the non-linear and linear behavior of a rectangular plate under uniform load producing large deflections (see APPENDIX C).

$$\sigma_{NL} = \begin{bmatrix} 0.5 * \sigma_L = 0.5 * \left(\frac{6 * M_{dent}}{t^2}\right) = \frac{3 * M_{dent}}{t^2} \ \ if\ AR > 1.5 \\ 0.6 * \sigma_L = 0.6 * \left(\frac{6 * M_{dent}}{t^2}\right) = \frac{3.6 * M_{dent}}{t^2} \ \ if\ AR \leq 1.5 \end{bmatrix}$$ **Eqn. 2-2-15**

Determine the material allowable, F_{allow}.

$$F_{allow} = \begin{bmatrix} F_{tu_{ult\_strain}} \ \ if\ \sigma_{MAX} = \sigma_{MAX,Pr} \\ F_{cu}\ otherwise \end{bmatrix}$$ **Eqn. 2-2-16**

Step 7

Note: For the Non-Linear analysis, it is assumed the dent has exceeded the yield point. Therefore, for tension loading, B-Basis Ftu cannot be used. Obtain the corresponding Ftu at the ultimate total strain value, e_u, per Figure 2-5 in Ref. [13]. For aluminum 2219-T62, the Ftu_{ult_strain} is 59 ksi.

The non-linear characteristics can only be used once. Do not use material non-linearity (Plastic Bending) and geometric non-linearity (reduced moment) together.

Calculate non-linear Margin of Safety, MS_{NL}.

Step 8

$$MS_{NL} = \frac{F_{allow} * TRF}{\sigma_{NL}} - 1$$ **Eqn. 2-2-17**

If MS_{NL} is positive, proceed to Stability Analysis in Section 2.3.

If MS_{NL} is negative, mitigate with the Open Hole Analysis in Section 2.2.4.

2.2.3.2 Non-Linear Analysis Flowchart

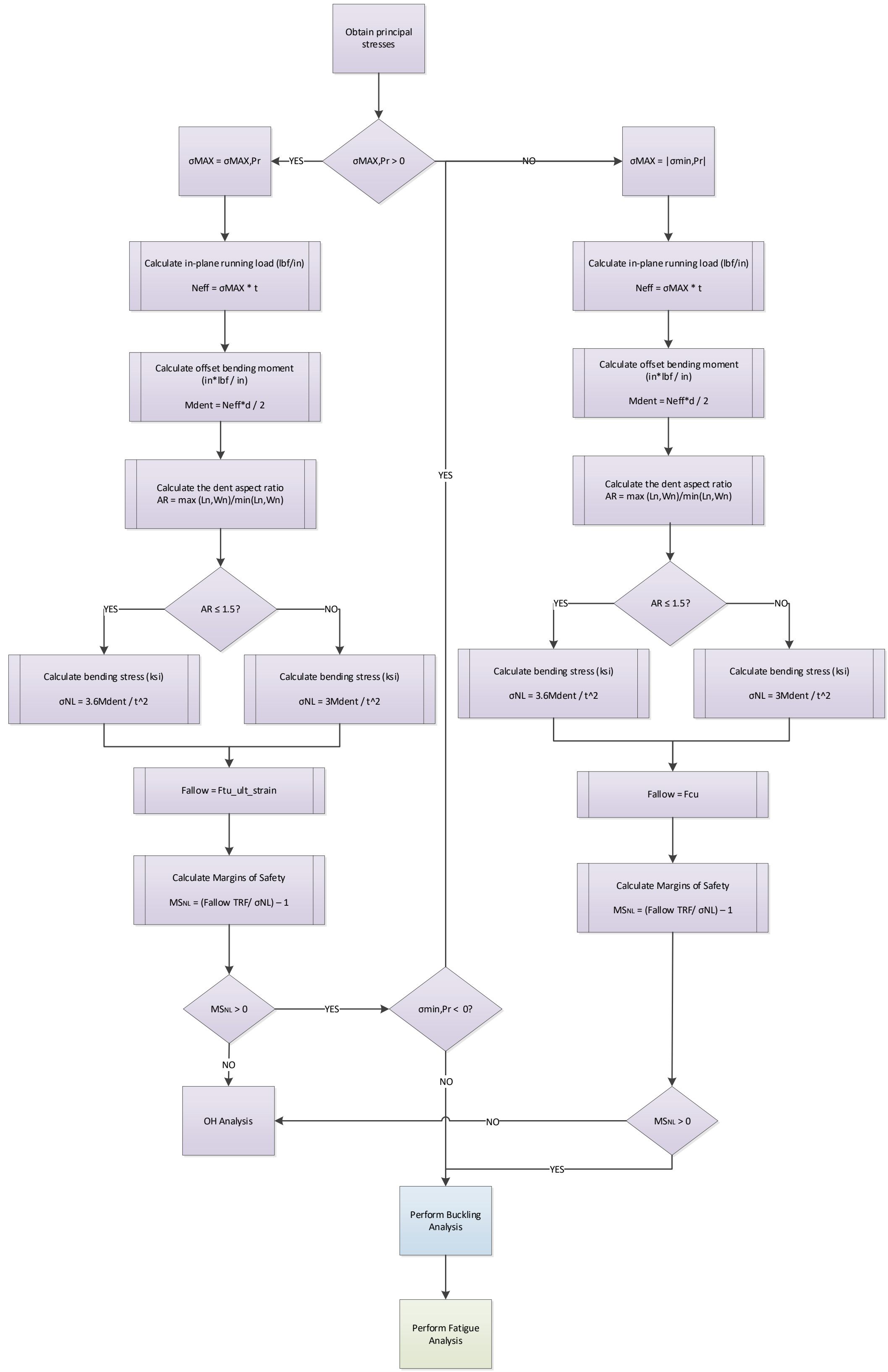

Figure 2-9 Non-Linear Static Analysis Flowchart

2.2.4 Open-Hole Procedure

The previous linear and non-linear methods assume the dented material is able to carry loads. If that assumption does not yield positive margins of safety, the final static analysis procedure is to assume the load is instead redistributed around the damage and the dent behaves as an open hole.

For an open hole in the far field area ($e_m/D \geq 2$), the following equation is an industry standard used to calculate the load redistribution for static analysis (and buckling analysis):

$$NSF = \frac{L}{L-D}$$

The Net Section Factor (NSF) is equivalent to a stress concentration factor local to the edge of the hole.

For $e_m = 2D$, the NSF becomes 1.25 and it is conservatively applied for every $e_m/D \geq 2$:

$$NSF = \frac{5D}{5D-D} = \frac{5D}{4D} = 1.25$$

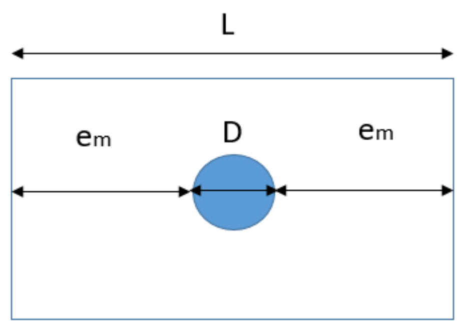

Figure 2-10 Open Hole in Far Field

When the dent is deep, the higher stress due to the dent depth is not reflected by the NSF because the higher stress occurs at the fore-aft edge as well as the center of the dent and it is not at a single corner. Therefore, for dents with a $0.5 \leq e_m/D < 2.0$, the NSF becomes oversimplified and un-conservative, which may lead to incorrect conclusions. In this case, the Cozzone assumption of non-linear bending stress due to the dent is to be combined with the in-plane stress, thereby replacing the NSF. Based on the Cozzone assumption, the non-linear bending stress is converted into an equivalent uniform in-plane stress by averaging the bending stress (see Figure 2-11):

$$\sigma_{equivalent} = \frac{(0+\sigma_{NL})}{2} = \frac{(0+3.6*Mdent/t\text{^}2)}{2} = 1.8\,\frac{Mdent}{t^2} \qquad \text{AR = 1.0 (hole)}$$

For a dent with an $e_m/D < 0.5$, the Net Section Factor exceeds 2.0, and falls outside the above assumptions. Proceed to the Reposition Flight Analysis in Section 2.5.

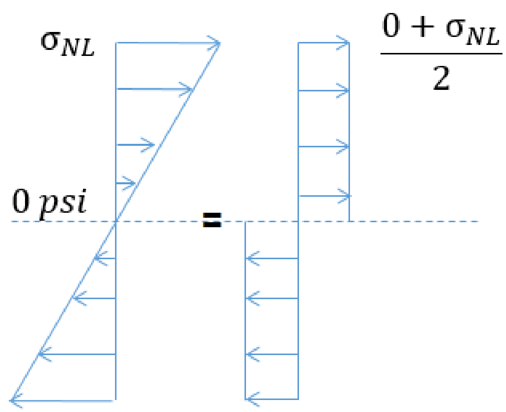

Figure 2-11 Cozzone Assumption on Non-Linear Bending Stress

2.2.4.1 Open-Hole Procedure Steps

Use dent geometry from Section 2.1.1 and 2.1.3.1.

Determine the e_m/D ratio:

Step 1

$$e_m/D = \frac{e_m}{\max(L_n\,, W_n)}$$ **Eqn. 2-2-18**

Step 2

In case of dents interaction, max (L_n, W_n) = D_{eff} and e_m = s_1. If $e_m/D > 2$, use e_m/D = 2.0.

Step 3

Obtain the most critical maximum and minimum principal stress for the dented area. The down-selection should be conducted based on margin of safety, which should include the effects of temperature, since a condition with lower stresses may result more critical due to higher temperature, compared to another with a higher stress but lower temperature.

Principal stresses can be found in the certification reports or can be calculated from running loads or stresses (in certification reports or extracted from Nastran f06 result file).

If $\sigma_{MAX,Pr} > 0 \; and \; \sigma_{min,Pr} < 0,$ repeat Step 3 through Step 7 with $\sigma_{MAX} = \sigma_{MAX,Pr}$ first (tension case) and then with $\sigma_{MAX} = |\sigma_{min,Pr}|$ (compression case).

If $\sigma_{MAX,Pr} \leq 0\,,\; \sigma_{MAX} = |\sigma_{min,Pr}|$ (compression case, no tension critical).

If $\sigma_{min,Pr} \geq 0\,,\; \sigma_{MAX} = \sigma_{MAX,Pr}$ (tension case, no compression critical).

Calculate the open hole equivalent stress, σ_{OH}.

Step 4

$$\sigma_{OH} = \begin{cases} NSF * \sigma_{MAX} = 1.25\,\sigma_{MAX}\,, & e_m/D \geq 2 \\ \sigma_{MAX} + 0.5 * \sigma_{NL} = \sigma_{MAX} + \dfrac{1.8 * Mdent}{t^2}, & 2 > e_m/D \geq 0.5 \end{cases}$$ **Eqn. 2-2-19**

If e_m/D is less than 0.5, proceed with the Reposition Flight Analysis in Section 2.5.

Determine the material allowable, F_{allow}.

Step 5

$$F_{allow} = \begin{bmatrix} F_{tu_{ult\_strain}} \; if \; \sigma_{MAX} = |\sigma_{MAX,Pr}| \\ F_{cu} \; otherwise \end{bmatrix}$$ **Eqn. 2-2-20**

Note: It is assumed the dent has exceeded the yield point. Therefore, for tension loading, B-Basis Ftu cannot be used. Obtain ($F_{tu_{ult\_strain}}$), which is the corresponding Ftu at the ultimate total strain threshold, ε_u, per Figure 2-5.

Calculate Open Hole Margin of Safety, MS_{OH}.

$$MS_{OH} = \frac{F_{allow} * TRF}{\sigma_{OH}} - 1 \qquad \textbf{Eqn. 2-2-21}$$

If MS_{OH} is positive, proceed to Stability Analysis in Section 2.3.

If MS_{OH} is negative, mitigate with the Reposition Flight Analysis in Section 2.5.

2.2.4.2 Open-Hole Procedure Flowchart

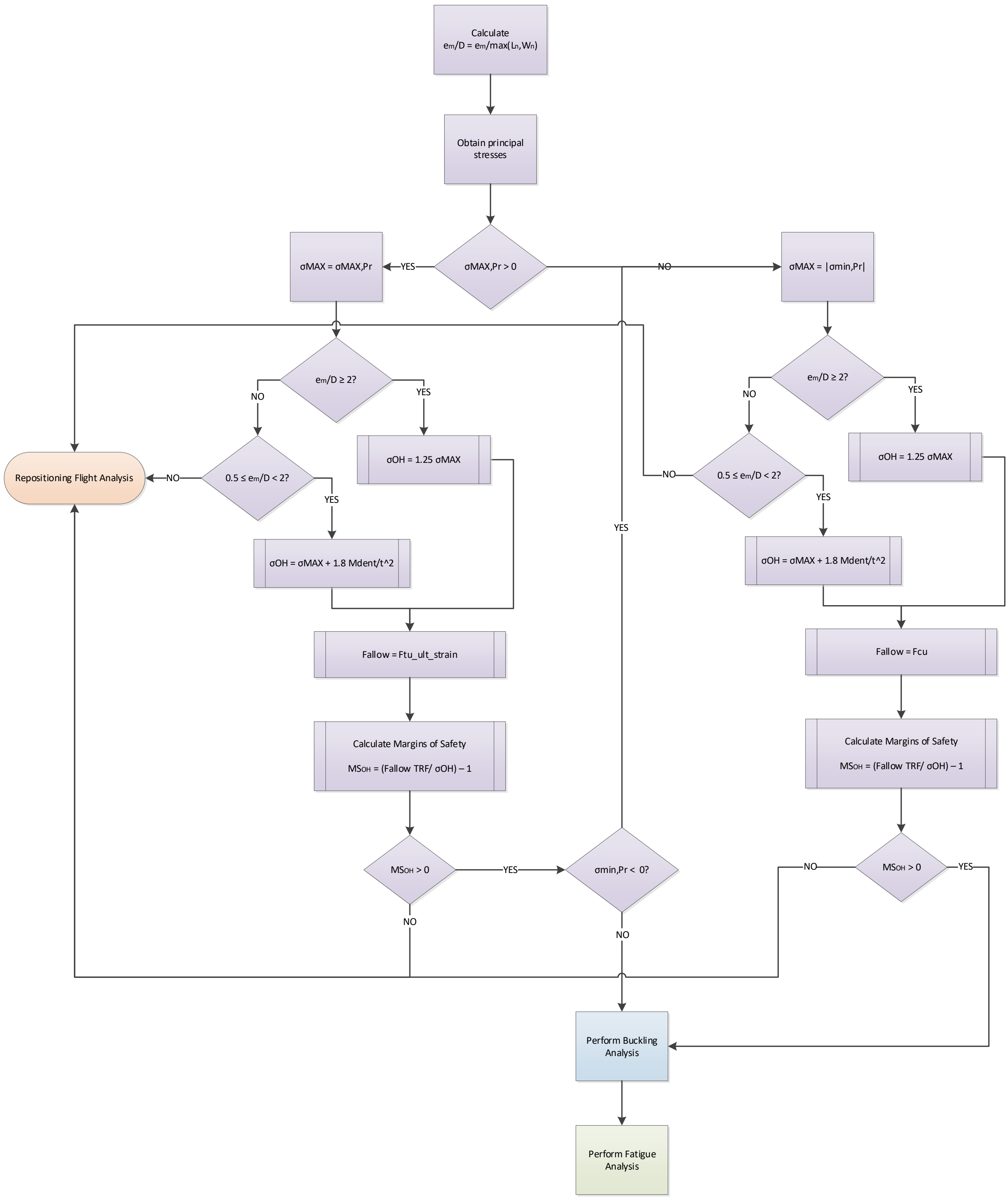

Figure 2-12 Open Hole Static Analysis Flowchart

2.3 STABILITY ANALYSIS

2.3.1 Background and Assumptions

The dented structure must be checked for buckling. Unless differently specified in the OEM Nacelle Program Requirements, buckling analysis shall be carried out using limit loads.

The type of stability analysis depends on how the dent is analyzed in the previous static check. If the dent is treated as an OH, a global and local buckling are carried out, otherwise, just a local stability is performed. A dent treated as an OH is a dent whose section is unable to carry any load therefore the dent represents a discontinuity in the D-Duct section.

The global buckling check is the D-Duct stability analysis where the D-Duct is treated as a circular cylinder with an inward acting radial pressure. The cross section of the D-Duct is reduced by the dent. The NSF defined in section 2.2.4.1 is used, with L = panel width and D = dimension of the dent aligned with the panel width. Refer to Figure 2-13 for geometry. The critical stress is then factorized by the NSF. Buckling curves in Ref. [2], C8.10, Figure C8.16, “Buckling Under External Radial Pressure” are used.

Based on the lipskin’s shape, we can define an outer skin and an inner skin. The geometrical quantities used in the global analysis are local to the dent. Therefore, depending on where the dent is located, the inner or outer skin dimensions (arc length and radius measured from the inlet centerline) are used. If the dent is on the hi-light, the lipskin area (inner or outer) with the highest load shall be considered.

The local buckling check is the dent stability analysis with the cross section of the curved dent. Buckling curves in ESOM in Ref. [6] for curved panels are used.

There is no limitation for (L_n, W_n, D_n) dimension to be used when the dent is not treated as an open hole (dent analyzed with linear or non-linear static method) and a local buckling analysis is carried out. For a dent treated as an open hole, a cut-off for (L_n, W_n, D_n) is used and a global D-Duct stability analysis is carried out in addition to the local buckling, following this approach:

1. Use max (L_n, W_n, D_n) dimension in line with the in-plane load.
2. Compare 3*max(L_n, W_n, D_n) to the panel size. If 3*max(L_n, W_n, D_n) > panel size, reject the fly-on.[1]
3. Analyze buckling of the D-Duct with dent
4. Analyze buckling of the local dent

Suggestions on panel size are provided in the next section 2.3.2. For lipskins, the panel size is the length of the D-Duct measured from the top joint to the fwd bulkhead to the lower joint to the inner barrel, see Figure 2-15.

Buckling is critical in compression, and as a result, the max compressive stress must be used $(\sigma_{min,Pr})$.

[1] The factor 3 is an agreed parameter within the Aftermarket Subject Matter Experts used as a cut-off for dent dimensions based on historical data of One-Offs cases.

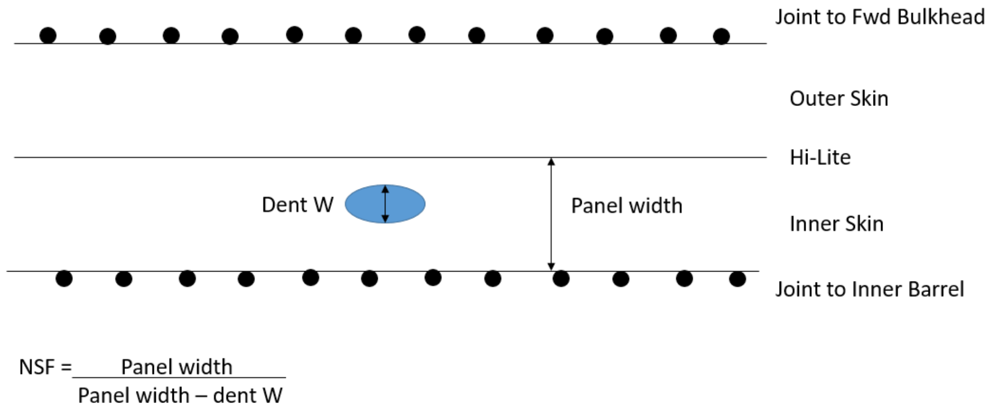

Figure 2-13 Panel Size for Global Buckling Analysis

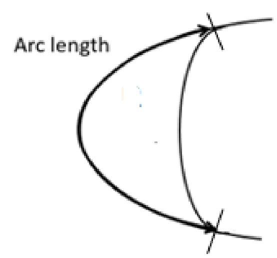

Figure 2-14 Panel Size for Buckling Cut-Off Check

2.3.2 Stability Analysis Procedure

2.3.2.1 Stability Analysis Steps

Use dent geometry from Section 2.1.1 and 2.1.3.1.

Step 1 Obtain the compressive skin stress, $\sigma_{min,Pr}$. See Step 2 in section 2.2.2.1. If $\sigma_{min,Pr} > 0$, the structure at the dent is not buckling critical, move to fatigue analysis in section 2.4.

Step 2 If Stability Analysis was accomplished with Open Hole analysis (dent treated as open hole), do the following check, otherwise go to Step 11:

Step 3 Determine if maximum dent dimension, L_n, W_n, or D_n, exceeds 1/3 times the panel's size. As panel size, take the length of the D-Duct measured from the top and bottom attachment of the forward bulkhead to the lipskin. For example, for V2500 and CRM56-5A/5B inlets, that measures 18" and for the B737 inlet is 16". See Figure 2-14.

$$Buckling\ Size\ Check = \begin{cases} \text{"Pass"}, & \max\left(L_n, W_n, D_n\right) < 1/3 * panel\ size \\ \text{"Fail"}, & otherwise \end{cases} \quad \textbf{Eqn. 2-2-22}$$

If "Pass", continue with Step 4, Global Buckling.

If "Fail", reject the fly-on.

Step 4 Obtain the panel width and radius.

Step 5 Calculate NSF = panel width / (panel width – dent width).

Step 6 Calculate the buckling stress:

$$\boldsymbol{\sigma_{buck} = NSF\ x\ \sigma_{min,Pr}} \quad \textbf{Eqn. 2-2-23}$$

Step 7 Obtain the elastic modulus at temperature.

Step 8 Refer to Ref. [2], Figure C8.16, "Buckling Under External Radial Pressure" to calculate the bucking coefficient Ky and the buckling allowable $\sigma_{c,cr}$:

$$\boldsymbol{\sigma_{c,cr} = \frac{K_y \pi^2 E}{12(1-\nu^2)}\left(\frac{t}{L}\right)^2} \quad \textbf{Eqn. 2-2-24}$$

$$\textbf{with } \boldsymbol{Z = \frac{L^2}{rt}\sqrt{(1-\nu^2)}} \quad \textbf{Eqn. 2-2-25}$$

where L is the length of the panel (inner skin or outer skin), r is the lipskin radius from the centerline and t is the lipskin thickness.

Step 9 Calculate the MS = $\frac{\sigma_{c,cr}}{\sigma_{buck}} - 1$

Step 10 If MS ≥ 0, go to Step 11, Local Buckling.

If MS < 0, reject the fly-on.

Calculate the buckling stress, σ_{buck}:

$$\sigma_{buck} = \begin{cases} \sigma_{min,Pr} + 0.5 * \sigma_{NL} = \sigma_{min,Pr} + \dfrac{1.8 * Mdent}{t^2}, d > t \;\; AND \; \dfrac{e_m}{D} < 2 \\ \qquad\qquad\qquad\qquad for\ every\ AR \\ \sigma_{min,Pr}, \quad otherwise \end{cases}$$ **Eqn. 2-2-26**

Step 11

Determine the compressive buckling coefficient, k_c and the shear buckling coefficient k_S from Ref. [6].

$$k_c \text{ and } k_S \text{ constraint} = \begin{cases} Fixed,\ d < t/2 \\ Simply\ Supported,\ otherwise \end{cases}$$ **Eqn. 2-2-27**

Step 12

In general, the major force on a lipskin is the normal force in hoop direction. For this reason, it is assumed that 80% of the compression stress comes from axial and 20% from shear. Under this hypothesis, it is assumed that the total buckling coefficient can be written as: k = 0.8 kc + 0.2 ksi.[2]

Obtain the material properties, F_{cy}, E, v.

Step 13

Step 14

Follow ESOM FB10-06, Ref. [6] for Curved Plate Buckling using the full dent arc length in Figure 2-4, calculated as follows:

$$dent\ arc\ length = \frac{2\theta}{360} 2\pi r$$ **Eqn. 2-2-28**

where $\theta = atan\left(\frac{\sqrt{2rd - d^2}}{r-d}\right)$ (radians)

Note that Eqn. 2-2-28 requires theta in degrees.

The dent arc length is the "b" in the buckling equation for $F_{cr,c}$.

Step 15

Follow the linear buckling procedure in Ref. [6], no plasticity equation is used. No cladding factor is added since the lipskins are not clad treated.

Calculate Buckling Margin of Safety per ESOM FB10-06, Ref. [6].

If MS ≥ 0, proceed to Fatigue Analysis in Section 2.4.

If MS < 0, reject the fly-on.

[2] This assumption is accepted by the Aftermarket Subject Matter Experts (DAEs and DERs)

2.3.2.2 Stability Analysis Flowchart

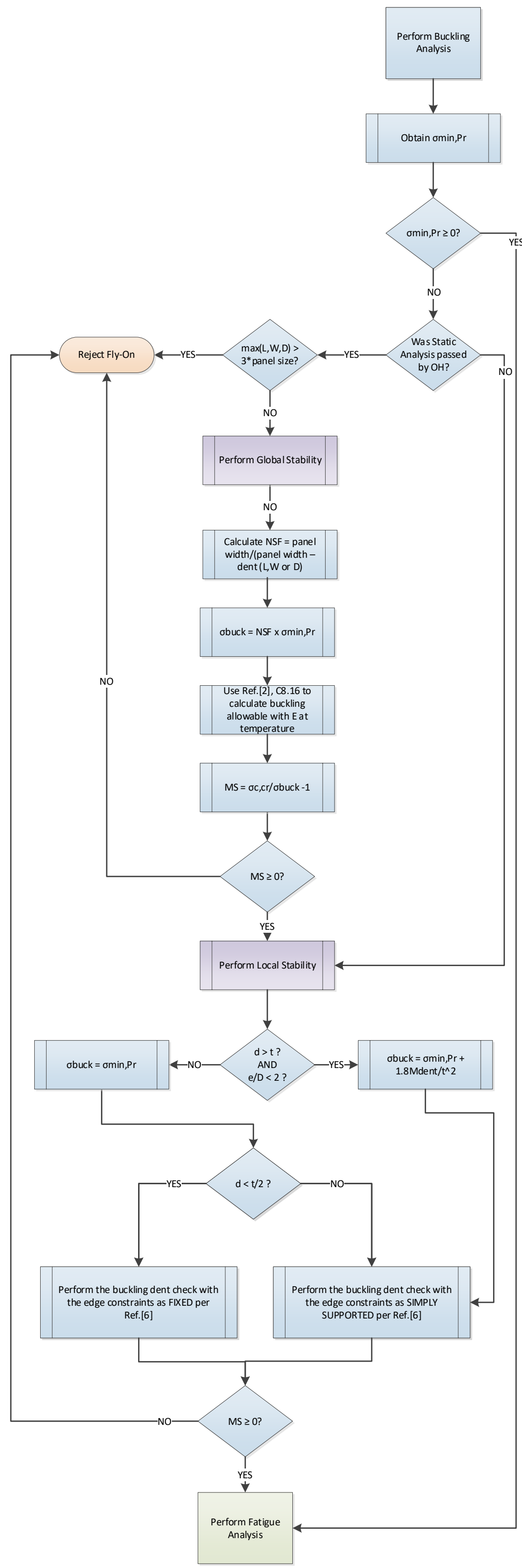

Figure 2-15 Stability Static Analysis Flowchart

2.4 FATIGUE ANALYSIS

A fatigue analysis of the dent is required to understand which disposition to provide to the customer for dents with positive margins for static and stability analysis and not substantiated through Repositioning Analysis, which allows just 2 FC.

The fatigue analysis can allow an un-repaired dent to be either temporary or permanent. To be permanent, a dent must meet full aircraft life with a scatter factor of 5. In addition, the dent needs to be assessed by the OEM aerodynamic group, which could provide a more stringent disposition.

When a dent does not meet full aircraft life, the intent of this ESOM is to use conservatisms to allow a temporary dent in an "as-is" condition. In this case, the life of the dented structure is calculated: the disposition is provided for whatever event between the calculated limited life and 2 years occurs first. If the 2-year event occurs before the calculated dent limited life but does not meet the requirements listed in Section 2.4.2, the disposition shall be written for a fly-on of 10 days, after which the structure must be repaired.

2.4.1 Permanent Dents

For fatigue analysis, use fatigue loads if available to calculate stresses.

Step 1 — If not available, take the ultimate stress and divide by 1.5 to obtain limit stress and multiply by 0.7. Start from stress calculate in Section 2.2 (ultimate).

Step 2 — The following factors are applied to the fatigue stresses, depending upon the dent geometry, which is:

- loads going thru the dent, where the dent is substantiated with linear or non-linear static analysis) or
- loads going around the dent, where the dent is substantiated with OH static analysis

Method	Linear Analysis	Non-Linear Analysis AR>1.5	Non-Linear Analysis AR≤1.5	OH
Kt	6 x d / (2t)	3.0 x d / (2t)	3.6 x d / (2t)	3.0

For dents analyzed with the liner method, for example, the Kt is calculated substituting Eqn. 2-2-7 in Eqn. 2-2-8 and Eqn. 2-2-8 in Eqn. 2-2-9:

$$\sigma_L = \frac{6*M_{dent}}{t^2} = \frac{6*N_{eff}*d/2}{t^2} = \frac{6*\sigma_{MAX}*t*d/2}{t^2} = K_t\ \sigma_{MAX}$$

Step 3 — with $K_t = \frac{6*t}{t^2}\frac{d}{2} = 6*\frac{d}{2t}$

Similar procedure is used to calculate the Kt for the non-linear case.

For a dent treated as an OH, the empirical 3.0 value for a hole in an infinite plate from Peterson in Ref. [1] is used.

Compare fatigue stress adjusted with the above factors to S/N curve for material at K_t = 1 and proper R (fatigue stress ratio) value.

Note that for legacy lipskins (up to the Boeing 787 Program), MMPDS fatigue curve and fatigue equations for Al2219-T851 with Kt = 2.0 are used (Figure 3.2.17.2.8(a) of MMPDS-07 in Ref.[13]), factorizing to account for Al2219-T851 vs. Al2219-T62 and dividing the stress by 2.0.

For new programs (from the Boeing 787 Program and up), the fatigue model for Al2219-T62 in RHR 06-0078 in Ref. [14] is used. After investigating the creep behavior of each Lipskin, it is deemed that the Lipskins are not creep critical and the combined fatigue and creep model is not used.
The TRFs used are program consistent, due to different consideration on the aging and hours of exposure of the material, which is program dependent.

Step 4 Reduce the fatigue allowable for temperature, surface finishing etc.

Step 5 Evaluate and obtain allowable cycles for the given maximum stress.

Step 6 Divide allowable cycles by scatter factor (SF) of 5

Step 7 Compare the calculated life of the dented structure with the required full life of the aircraft. Permanent dents must meet full aircraft life (allowable cycles/5 > aircraft life cycles) Permanent dents do not require repeated inspections.

If full aircraft life is not obtained, dent is good for allowable cycles/5 or 2 years maximum whichever occurs first. The 2-year disposition is dictated by most of the OEMs on repairs not reaching the full aircraft life and therefore applied to dents as conservative approach.

Step 8 If 2-year event occurs first, go to temporary dent fatigue assessment in section 2.4.2

2.4.2 Temporary Dents

A temporary dent disposition can be provided if the following criteria are met. These criteria originate from SRM common practice across programs and are also based on history of cases where the reported dents left in "as-is" condition did not evolve or worsen. For this reason, the below criteria are conservative and accepted by the Aftermarket Subject Matter Experts.

Step 1 Obtain dent geometry in Section 2.1

Step 2 Determine the dent radius of curvature r (see Eq. 2-5 in Step 3 of section 2.1.4.1)

Step 3 Ratio of dent in-plane dimension over dent depth $\frac{\min(L_n, W_n)}{d_n} \geq 10$

Step 4 Dent depth $d < 0.3"$

Step 5 r > 0.25"

Step 6 Maximum fatigue stress level is ≤ 19 ksi and R ≥ 0.00

If above criteria are met, dent is good for 2 years with 6 months visual inspection using 10x magnification.

If the dent does not pass either of the above criteria and there are no cracks, we can allow the aircraft to fly-on for 10 days.

2.5 ANALYSIS FOR RE-POSITIONING FLIGHTS (LIPSKIN ONLY)

2.5.1 Background and Assumptions

The re-positioning flight analysis is reserved for severe dent damages. This method modifies the standard dent method, which is intended for permanent or long-term temporary dispositions, to a method capable of allowing larger dent damages for short duration fly-on. These analyses are only acceptable for positioning flights and are limited to a maximum of 2 FC's. Any load case eliminations, such as EAI-On or elimination of MMEL+1 condition require DAE approval. The analysis maximizes the non-linear allowable for lipskin single load path condition, as well as the admissible elastic-plastic structural behavior.

2.5.2 Re-Positioning Flight Analysis Procedure

2.5.2.1 Re-Positioning Flight Analysis Procedure Steps

Step 1 Use dent geometry from Section 2.1.1 and 2.1.3.1.

Step 2 Perform Interaction Check per Section 2.1.3. If dents were found to interact, use the appropriate assumed effective dimensions.

Step 3 Perform Deformation Check per Section 2.1.4.

Step 4 Obtain the most critical maximum and minimum principal stress for the dented area.

If $\sigma_{MAX,Pr} > 0 \; and \; \sigma_{min,Pr} < 0,$ repeat Step 5 through Step 9 with $\sigma_{MAX} = \sigma_{MAX,Pr}$ first (tension case) and then with $\sigma_{MAX} = |\sigma_{min,Pr}|$ (compression case).

If $\sigma_{MAX,Pr} \leq 0$, $\sigma_{MAX} = |\sigma_{min,Pr}|$ (compression case, no tension critical).

If $\sigma_{min,Pr} \geq 0$, $\sigma_{MAX} = \sigma_{MAX,Pr}$ (tension case, no compression critical).

Step 5 Calculate the effective in-plane running load, N_{eff}. See Step 3 in section 2.2.3.1 (Eq. 2-2-12).

Step 6 Calculate the F_{allow}. See Step 7 in section 2.2.3.1 (Eq. 2-2-16).

Step 7 The Repositioning Analysis aims to reduce the conservatisms used in all previous analyses. It is assumed that the dented structure can sustain the bending stress up to the optimized dent depth d_{opt} (see Figure 2-16). We define the optimized dent depth, d_{opt} as the depth where the linear analysis margin of safety = 0 combining Eq. 2-2-11, 2-2-9 and 2-2-8:

Step 8

$$MS_L = 0 = \frac{F_{allow} * TRF}{\left(3 * N_{eff} * d\right) / t^2} - 1 \qquad \textbf{Eqn. 2-2-29}$$

$$d_{opt} = \frac{F_{allow} * TRF * t^2}{3 * N_{eff}} \qquad \textbf{Eqn. 2-2-30}$$

If the optimized dent depth exceeds the actual dent depth, $d_{opt} \geq d_n$, perform Non-Linear analysis in Section 2.2.3.1 using d_n as dent depth. If $MS_{NL} \geq 0$, perform Buckling analysis in

Section 2.3.2 using d_n as dent depth and the compression stress $\sigma_{MAX} = |\sigma_{min,Pr}|$, otherwise reject the fly-on. If $\sigma_{min,Pr} \geq 0$, the dent is not buckling critical, and the dent is acceptable "as-is" for 2 FC. If $\sigma_{min,Pr} < 0$ and the buckling MS ≥ 0, the dent is acceptable "as-is" for 2 FC, otherwise, reject the fly-on.

Step 9

If the optimized dent depth is less than the actual dent depth, $d_{opt} < d_n$, perform Non-Linear analysis in Section 2.2.3.1 using d_{opt} as dent depth. If $MS_{NL} \geq 0$, go to Step 10, otherwise reject the fly-on.

Step 10

It is assumed that the dented structure can sustain the bending stress up to the optimized dent depth d_{opt}. At this depth, we define an optimized flat dent size b_{opt}, which can be seen in Figure 2-16.

Step 11

Perform buckling analysis with the optimized buckling size b_{opt} determined as follows:

$$b_{opt} = \left(1 - \frac{d_{opt}}{d}\right) * avg(L_n, W_n) \qquad \textbf{Eqn. 2-2-31}$$

Note: it is conservative to consider the max L_n instead of the average (L_n, W_n) for buckling area.

In case of dents interaction, avg (L_n, W_n) = D_{eff}.

Step 12

If $\sigma_{min,Pr} \geq 0$, the dent is not buckling critical, and the dent is acceptable "as-is" for 2 FC. If $\sigma_{min,Pr} < 0$, determine the buckling stress, σ_{buck}, using Eq.2-2-26 for every AR:

$$\sigma_{buck} = \begin{cases} \sigma_{min,Pr} + 0.5 * \sigma_{NL} = \sigma_{min,Pr} + \dfrac{1.8 * Mdent}{t^2}, dopt > t \ \ AND \ \dfrac{e_m}{D} < 2 \\ \qquad\qquad\qquad\qquad\qquad\qquad for\ every\ AR \\ \qquad\qquad \sigma_{min.Pr}, \qquad otherwise \end{cases} \qquad \textbf{Eqn. 2-2-32}$$

Step 13

where $M_{dent} = \frac{N_{eff}\, d_{opt}}{2}$

Determine the compressive buckling coefficient, k_c, from ESOM FB10-05 in Ref. [6].

Step 14

Step 15

$$k_c\ constraint = Simply\ Supported\ Curve \qquad \textbf{Eqn. 2-2-33}$$

The Flat Plate Buckling analysis is performed per ESOM FB10-05, Ref. [6].

If MS is positive, the dent is acceptable for 2 FC.

If MS is negative, reject the fly-on.

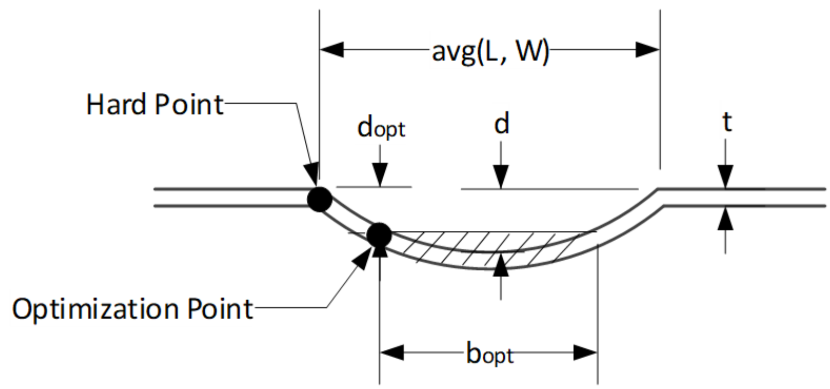

Figure 2-16 Repositioning Flight Dent Geometry Variables

2.5.2.2 Re-Positioning Flight Analysis Procedure Flowchart

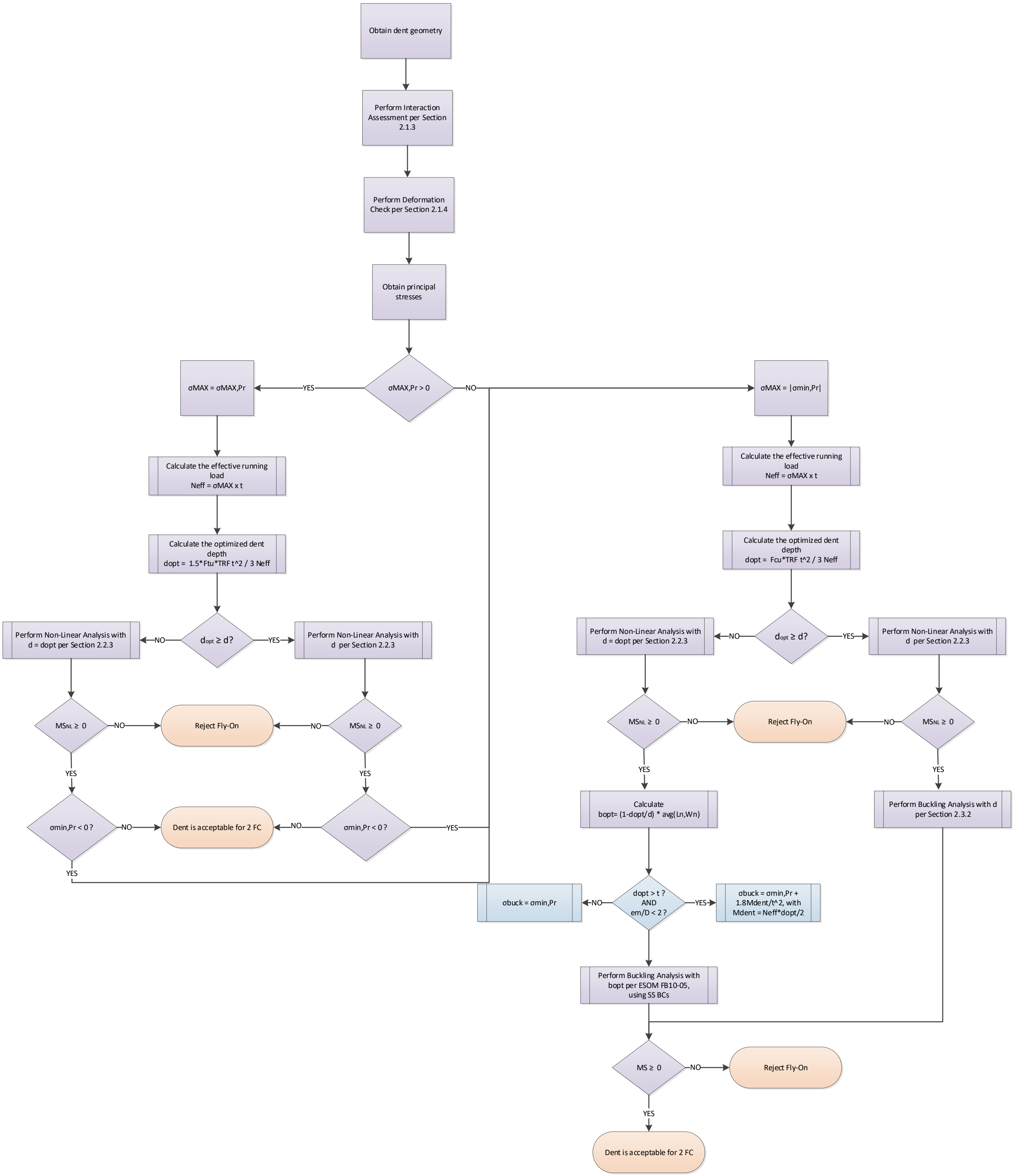

Figure 2-17 Re-Positioning Flight Analysis Flowchart

3.0 APPENDIX A: HOLES INTERACTION

We want to calculate the stress concentration factor due to the interaction between two holes at point A as shown in Figure 3-1.

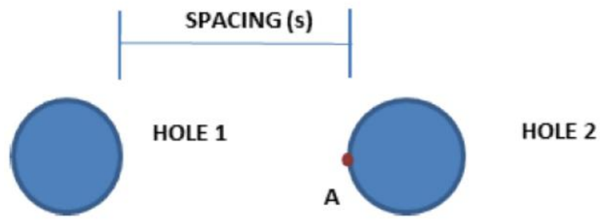

Figure 3-1 Equal diameter holes interaction (fatigue)

The following Peterson [Ref. 1] stress concentration equation is used to calculate the interaction between two dents (refer to Figure 3-2):

$$\boldsymbol{\sigma_\theta = \frac{1}{2}\sigma\left(1+\frac{a^2}{r^2}\right) - \frac{1}{2}\sigma\left(1+\frac{3a^4}{r^4}\right)cos2\theta}$$ **Eqn. 3-1**

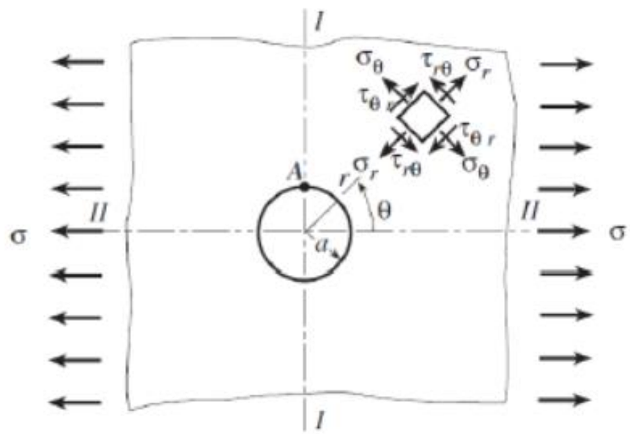

Figure 4.3 Infinite thin element with hole under tensile load.

Figure 3-2 Infinite thin elements with a hole under tensile loads (Peterson)

This equation writes the tangential stress σ_θ at a point with distance r from the center of the hole as a function of the far field stress σ, θ coordinate and a, with "a" being the radius of the hole.

Referring to Figure 3-1, the stress concentration factor at A ($K_{t2,A}$) is always 3.0. The stress concentration factor $K_{t1,A}$ due upon the interaction with hole 1 varies with the distance r to hole 2 and it is calculated using Eq.4-1 written as:

$$\frac{\sigma_\theta}{\sigma} = \frac{1}{2}\left(1+\frac{a^2}{r^2}\right) - \frac{1}{2}\left(1+\frac{3a^4}{r^4}\right)cos2\theta = K_{t1,A}$$

The total stress concentration factor due to the interaction is:

$K_{t,total} = K_{t1,A} \times K_{t2,A}$

For different hole spacing "s" (refer to Figure 3-1), we obtain the $K_{t,total}$ values as in Table 3-1. Considering the chart in Figure 3-3 and Table 3-1, above 1.5D there is no interaction between the two holes since $K_{t,total}$ approaches 3.0 (the difference between the $K_{t,total}$ at 1.5D and 2.5D is 4% (< 5%))

Table 3-1 Stress concentration factors calculation

r	s	K_{t1A}	K_{t2A}	$K_{t,total}$
a	0	3	3	9
1.125a	0.0625D	2.33	3	6.99
1.25a	0.125D	1.93	3	5.80
1.5a	0.25D	1.52	3	4.56
2a	0.5D	1.22	3	3.66
3a	1D	1.07	3	3.22
4a	1.5D	1.04	3	3.11
5a	2D	1.02	3	3.07
6a	2.5D	1.02	3	3.05
7a	3D	1.01	3	3.03
8a	3.5D	1.01	3	3.02
9a	4D	1.01	3	3.02

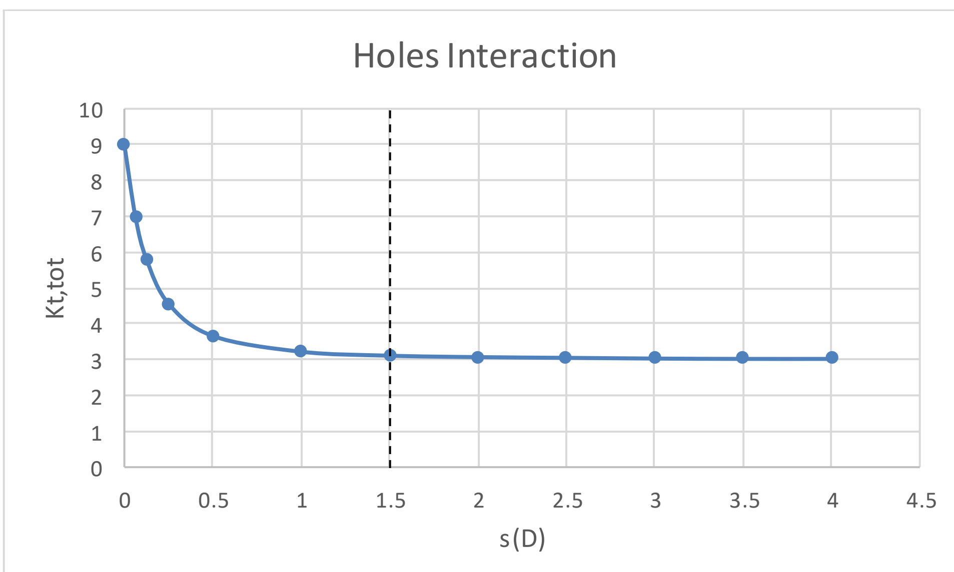

Figure 3-3 Stress concentration factor

4.0 APPENDIX B: DENT IN LIPSKIN

In this APPENDIX, a FEM correlation to the stress at the dent calculated using the offset moment in Eq. 2-2-9 is presented. This correlation shows that the bending stress alone captures the stress at the dent, without adding the in-plane stress components, for dent depths up to the thickness of the lipskin.

The lipskin segment FEM model in Ref. [9] is used, converted in Nastran format (see files *Lipskin_Shallow_Dent.bdf* and *Lipskin_Mild_Dent.bdf*). The lipskin is characterized by a thickness of 0.068" in the field and has the geometries of the A220.

A shallow dent with a depth equal to 0.03" and a diameter of 2" is created. The lipskin segment is constrained at his boundaries with fixed edge conditions and a pressure of 37.13 psi is applied (which typical of a burst duct pressure).

The FEM results with the above inputs are shown in Figure 4-1 (fringe plot of Maximum principal stress). An average of 19,500 psi can be calculated as field stress. Starting from this value, following the method is Section 2.2.2, we can calculate:

Running load:

$$N_{eff} = \sigma_{MAX} * t = 19{,}500\ x\ 0.068 = 1{,}323\ lb/in$$

Dent offset moment:

$$M_{dent} = \frac{N_{eff} * d}{2} = 1{,}323\ x \frac{0.03}{2} = 19.89\ lb * in/in$$

Bending stress:

$$\sigma_L = \frac{6 * M_{dent}}{t^2} = 6 * \frac{19.89}{(0.068)^2} = 25{,}808\ psi$$

The bending stress is in agreement with the peak dent stress calculated by the FEM (average of 26,500 and 24,700 = 25,808 psi).

If we add the in-plane stress, we obtain:

$$\sigma = 25{,}808 + 19{,}500 = 45{,}308\ psi$$

which does not match with the peak stress calculated by the FEM, resulting to be over-conservative.

With a dent depth equal to the thickness of the lipskin (mild dent), we obtain:

Dent offset moment:

$$M_{dent} = \frac{N_{eff} * d}{2} = 1{,}323\ x \frac{0.068}{2} = 44.98\ lb * in/in$$

Bending stress:

$$\sigma_L = \frac{6 * M_{dent}}{t^2} = 6 * \frac{44.98}{(0.068)^2} = 58{,}367\ psi$$

which is above the 32,950 psi predicted by the FEM. Adding the in-plane stress would bring to a stress of 77,867 psi.

Monitoring the directional stress in hoop direction (x-stress component), which is the major stress component in a pressurized lipskin, we can draw the same conclusions (see Figure 4-3 for directional stress, shallow dent and Figure 4-4 for directional stress, mild dent, where the hoop stress is 99% of the Max principal).

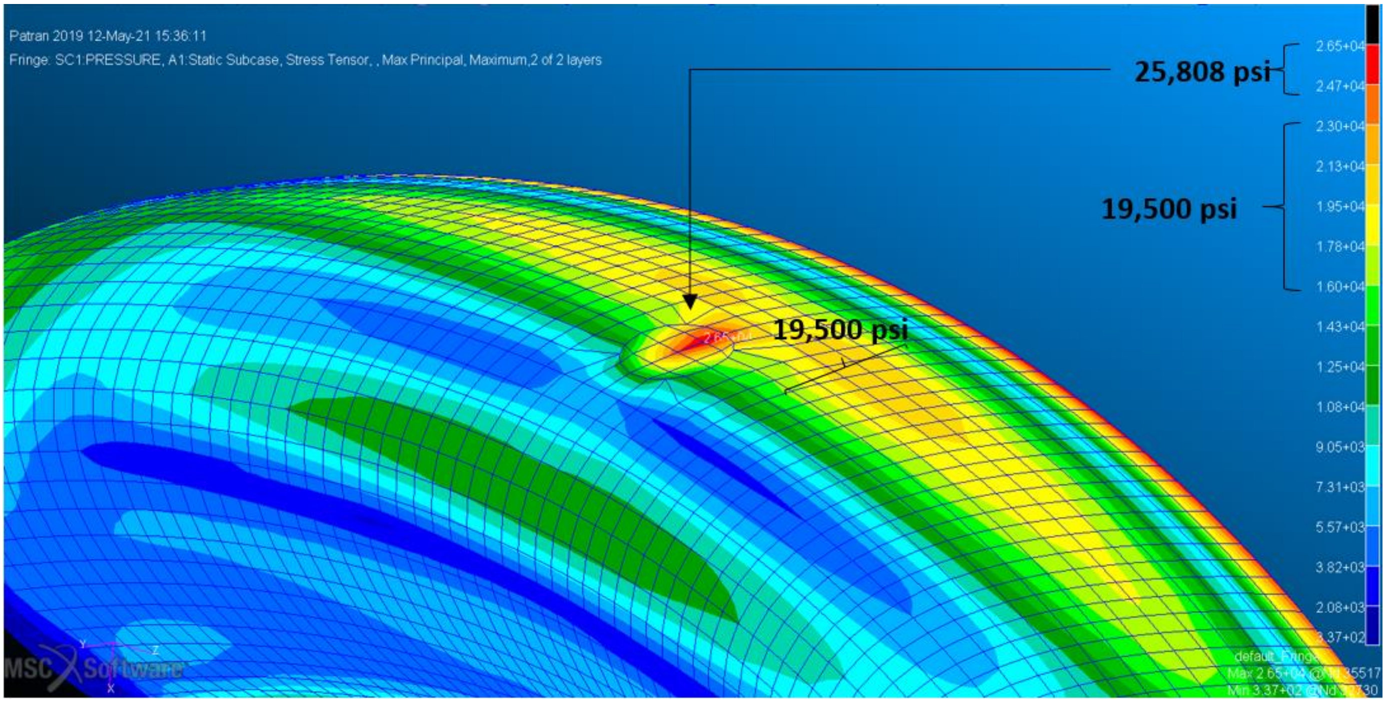

Figure 4-1 Shallow Dent in Lipskin (d<t/2) – Max Principal Stress

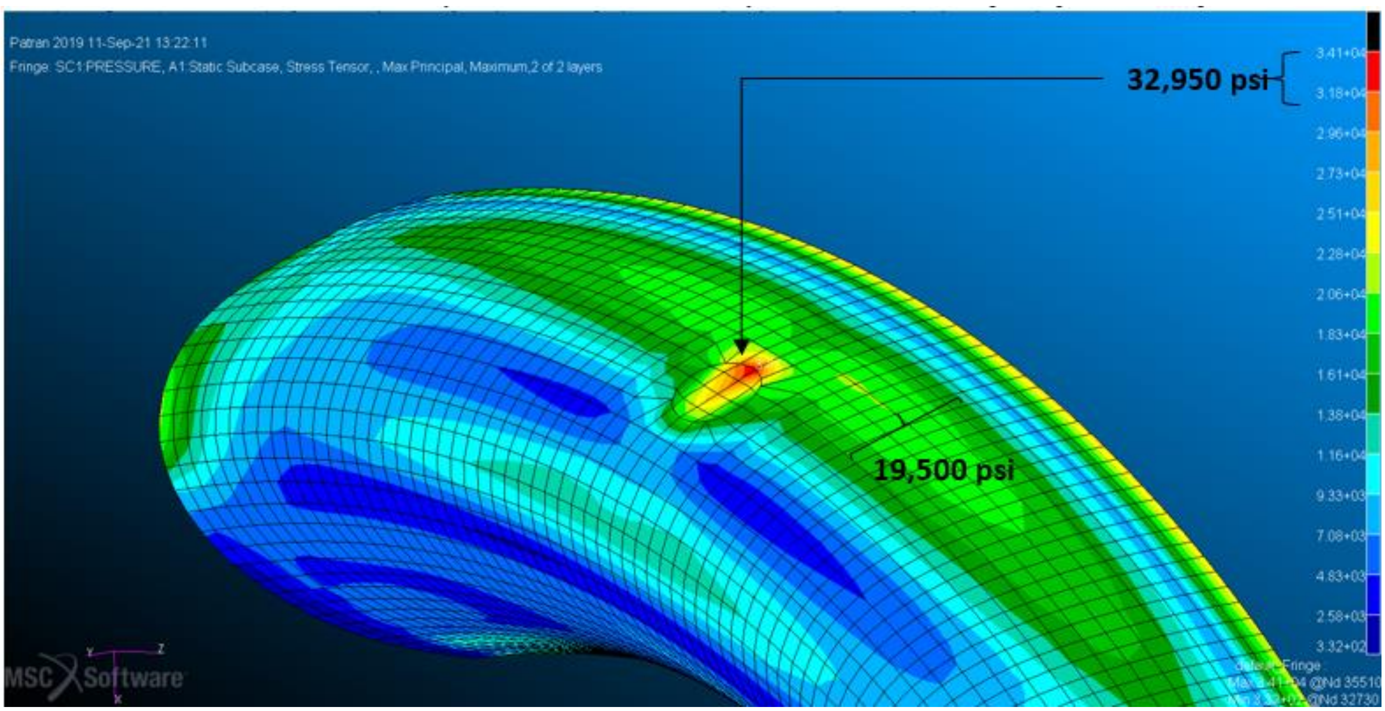

Figure 4-2 Mild Dent in Lipskin (d=t) – Max Principal Stress

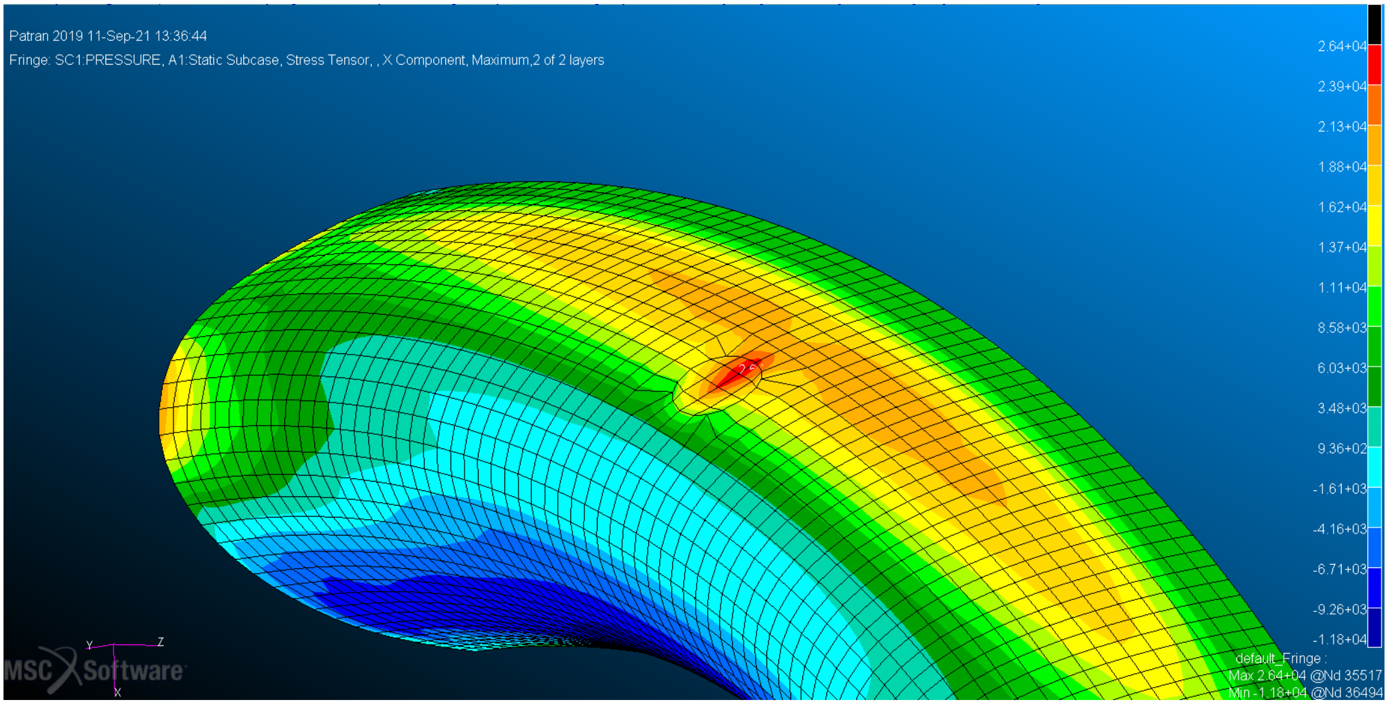

Figure 4-3 Shallow Dent in Lipskin (d<t/2) – Hoop Stress

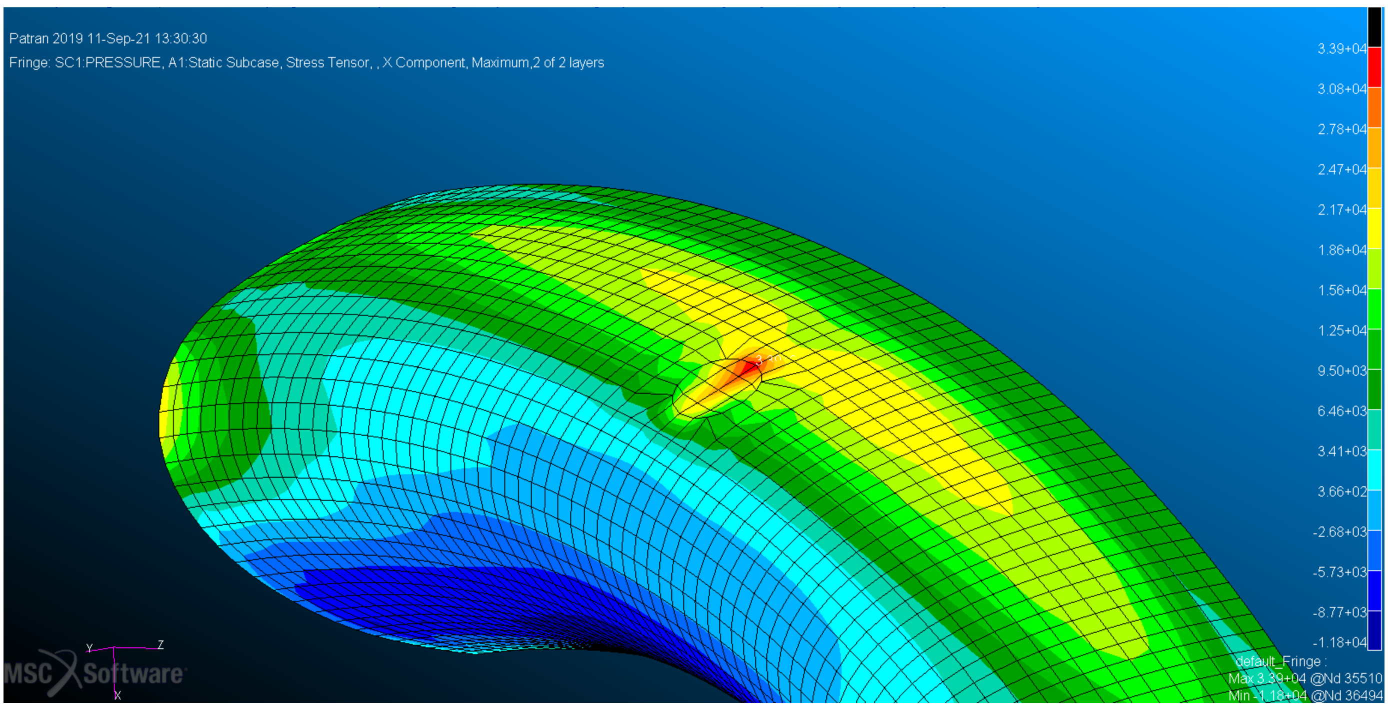

Figure 4-4 Mild Dent in Lipskin (d=t) – Hoop Stress

5.0 APPENDIX C: LINEAR VS. NON-LINEAR BENDING STRESSES

For the linear vs. non-linear bending stress equation, the following assumptions are used:

- For the non-linear evaluation, the “Held and not fixed” boundary condition is used since the lipskin or the face sheet to which the method is applied is not free to rotate
- The comparison is performed for aspect ratio a/b from 1 to 2
- Al 2219-T62 is used for the evaluation
- The bending stress is calculated as total stress minus the diaphragm stress:
  bending stress = σ (sigma) – σ_d (sigma)

The following nomenclature is used:

a = longer edge of the plate (in)

b = shorter edge of the plate (in)

q = uniform pressure (psi)

E = 10.5E+06 Young’s modulus for Al2219-T62 at RT (psi)

t = 0.07 nominal thickness (in)

σ_d = diaphragm stress (psi)

σ = total stress (psi)

Non-Linear Analysis for Bending Stress

Considering Ref. [5], page 452, we can calculate for a rectangular plate under uniform load producing large deflections:

a (in)	b (in)	a/b	qb^4/Et^4	σ_d b^2/Et^2	σ_d (psi)	σ b^2/Et^2	σ (psi)	bend stress (psi)
1	1	1	0.0397	0.0022	114	0.0123	620	506
1.5	1.5	1	0.2008	0.0112	257	0.061	1396	1139
2	2	1	0.6347	0.0355	457	0.1929	2482	2025
2.5	2.5	1	1.5495	0.0868	714	0.471	3878	3164
3	3	1	3.2129	0.1799	1029	0.9769	5584	4555
1.5	1	1.5	0.0397	0.0034	173	0.0142	731	558
2	1.33	1.5	0.1241	0.0106	308	0.0449	1300	992
2.5	1.67	1.5	0.3085	0.0260	481	0.1097	2032	1551
3	2	1.5	0.6347	0.0538	692	0.2275	2926	2234
3.5	2.33	1.5	1.1691	0.0997	942	0.4214	3982	3040
4	2.67	1.5	2.0159	0.1701	1231	0.7189	5201	3970
2	1	2	0.0397	0.0041	211	0.0155	795	584
2.5	1.25	2	0.0968	0.0100	329	0.0377	1242	913
3	1.5	2	0.2008	0.0207	474	0.0782	1789	1315
3.5	1.75	2	0.3720	0.0384	645	0.1449	2435	1790
4	2	2	0.6347	0.0655	842	0.2473	3180	2338
4.5	2.25	2	1.0166	0.1049	1066	0.3961	4025	2959

For the linear evaluation, two conditions are analyzed, the simply supported and the fixed boundary condition.

Linear Analysis for Bending Stress – Simply Supported

Considering the assumptions and equation Table 11.4 of Ref. [5], we can calculate for simply supported boundary condition:

a	b	a/b	beta	σ (psi) - center of plate	qb^2/t^2
1	1	1	0.2874	587	2041
1.5	1.5	1	0.2874	1320	4592
2	2	1	0.2874	2346	8163
2.5	2.5	1	0.2874	3666	12755
3	3	1	0.2874	5279	18367
1.5	1	1.5	0.4851	990	2041
2	1.33	1.5	0.4851	1751	3610
2.5	1.67	1.5	0.4851	2761	5692
3	2	1.5	0.4851	3960	8163
3.5	2.33	1.5	0.4851	5375	11079
4	2.67	1.5	0.4851	7058	14549
2	1	2	0.6102	1245	2041
2.5	1.25	2	0.6102	1946	3189
3	1.5	2	0.6102	2802	4592
3.5	1.75	2	0.6102	3814	6250
4	2	2	0.6102	4981	8163
4.5	2.25	2	0.6102	6304	10332

Linear Analysis for Bending Stress – Fixed

Considering the assumptions and equation Table 11.4 of Ref. [5], we can calculate for fixed boundary condition:

a (in)	b (in)	a/b	beta	σ (psi) - center of plate	qb^2/t^2
1	1	1	0.1386	283	2041
1.5	1.5	1	0.1386	636	4592
2	2	1	0.1386	1131	8163
2.5	2.5	1	0.1386	1768	12755
3	3	1	0.1386	2546	18367
1.5	1	1.5	0.219	447	2041
2	1.33	1.50	0.219	791	3610
2.5	1.67	1.50	0.219	1246	5692
3	2	1.50	0.219	1788	8163
3.5	2.33	1.50	0.219	2426	11079
4	2.67	1.50	0.219	3186	14549
2	1	2.00	0.2472	504	2041
2.5	1.25	2	0.2472	788	3189
3	1.5	2	0.2472	1135	4592
3.5	1.75	2	0.2472	1545	6250
4	2	2	0.2472	2018	8163
4.5	2.25	2	0.2472	2554	10332

Non-Linear vs. Linear Stress Comparison

Comparing the non-linear stress to the linear with different boundary conditions, it can be noticed that the non-linear stress is closer to the linear stress calculated using simply supported boundary conditions.

Arbitrarily calculating the linear stress as 80% of the stress with simply supported condition plus 20% of the stress with fixed condition, a ratio between the non-linear to linear stress can be written ("Ratio" in Table below).

For a/b ≤ 1.5, it is reasonable to use a factor of 0.6 on the linear bending stress so that:

Bending stress = $0.6*6M_{dent}/t^2 = 3.6*M_{dent}/t^2$

For a/b > 1.5, use a factor of 0.5 on the linear bending stress so that:

Bending stress = $0.5*6M_{dent}/t^2 = 3*M_{dent}/t^2$

For a/b = 1, the stress at the center of the plate is identical to the non-linear stress at the center of the long edge, "held and fix" boundary condition, which is questionable. The 0.6 factor is used for conservatism.

a (in)	b (in)	a/b	Linear σ (psi) SS	Linear σ (psi) Fixed	Linear σ (psi) 80%SS+20%F	Non-Linear σ (psi) "Held and not fixed"	Ratio
1	1	1	587	283	526	506	0.96
1.5	1.5	1	1320	636	1183	1139	0.96
2	2	1	2346	1131	2103	2025	0.96
2.5	2.5	1	3666	1768	3286	3164	0.96
3	3	1	5279	2546	4732	4555	0.96
1.5	1	1.5	990	447	881	558	0.63
2	1.33	1.50	1751	791	1559	992	0.64
2.5	1.67	1.50	2761	1246	2458	1551	0.63
3	2	1.50	3960	1788	3526	2234	0.63
3.5	2.33	1.50	5375	2426	4785	3040	0.64
4	2.67	1.50	7058	3186	6283	3970	0.63
2	1	2	1245	504	1097	584	0.53
2.5	1.25	2	1946	788	1714	913	0.53
3	1.5	2	2802	1135	2469	1315	0.53
3.5	1.75	2	3814	1545	3360	1790	0.53
4	2	2	4981	2018	4389	2338	0.53
4.5	2.25	2	6304	2554	5554	2959	0.53

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