THE INFLUENCE OF LOAD AND DEFORMATION ON THE FRACTURE BEHAVIOR OF SPECIMENS AND STRUCTURES

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OVERVIEW

The standard damage tolerance methods for the evaluation of fracture properties and the prediction of structural failure are mainly based on classical LEFM principles. Thereby, only the influence of the load is taken into account, which may significantly under- or overestimate the stress intensity factor of a cracked component. An accurate analysis is performed by the consideration of both, the load and the deformation behaviour of the cracked configuration.

The consideration of both the load and deformation behaviour is taken into account if plasticity effects have to be investigated. This may occur for thin walled structures even if the global stress level is far below the yield stress. However it may also be dependent on the local structural behaviour, where the application of a simplified crack case leads to erroneous results.

A large number of different configurations has been analysed during the last years with findings related to the

- evaluation of test results beyond the validity of standards requirements
- consideration of global or local plasticity effects in surface crack configurations
- analysis of complex structural conditions
- and special features of COPV

These configurations include all kinds of materials as titanium, aluminium or steel.

1. SELECTION OF K_I SOLUTION FOR STRUCTURE ASSESSMENT

The bosses of satellite propellant tanks, which are produced by net-shape forming of sheets, are joined to the membrane by polar welds. Due to the lack of penetration analysis of this polar weld, a stress intensity factor solution is selected. No standard solution for this kind of geometry exists and therefore an alternative solution has to be applied.

Four different crack cases from [1] are investigated with respect to the applicability for this kind of problem. The crack geometry of these cases are summarised in TAB. 1, a schematic presentation is given in FIG. 1 and FIG. 2.

Crack Case	a [mm]	c [mm]	a/c
SC01	0.85	4.25	0.2
SC03	0.85	4.25	0.2
SC06	0.85	-	-
TC02	-	0.85	-

TAB. 1: Crack Case Selection

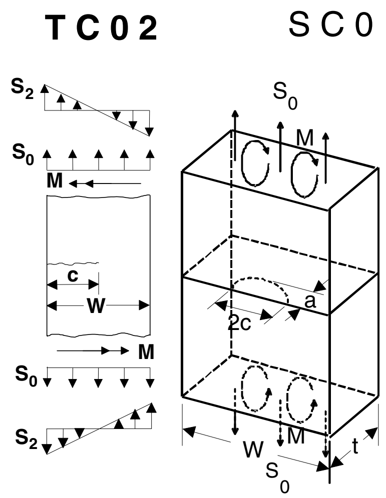

FIG. 1: Flat Plate Crack Cases

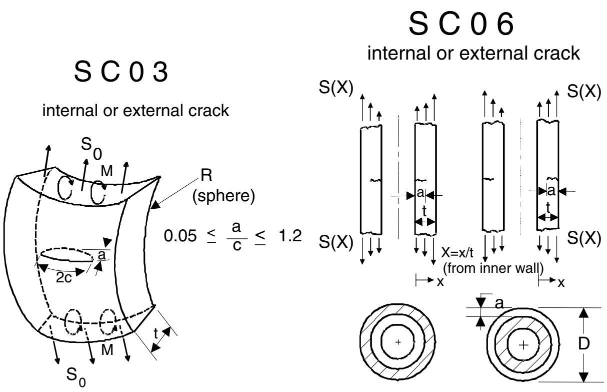

FIG. 2: Sphere- and Cylinder Crack Case

To check the validity of the different analytical solutions a FE analysis of the polar weld with a circumferential surface crack is performed. The discretisation and the details of the crack configuration are shown in FIG. 3 and FIG. 4

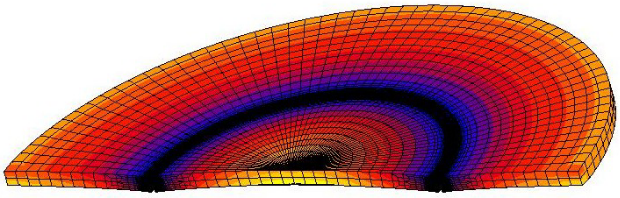

FIG. 3: FE-Mesh of Polar Weld with Circumferential Surface Crack

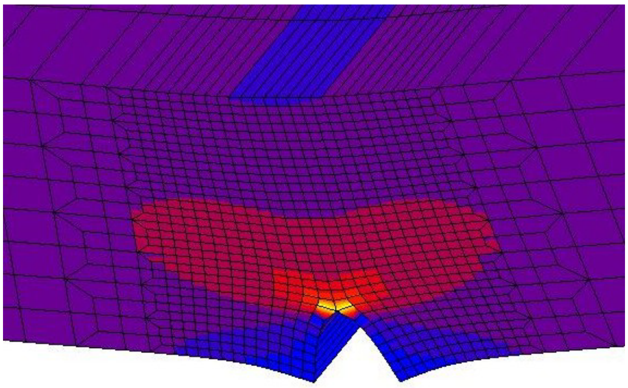

FIG. 4: FE-Mesh of Polar Weld with Circumferential Surface Crack (Detail)

The comparisons of the results from the different analytical approaches with the one from the FE analysis are shown in FIG. 5. The FE analysis results are evaluated for the node path ahead of the crack tip. Under consideration of equation (1), which is applied for the comparison with the analytical solutions, it is apparent that SC01, SC03 and TC02 represent the actual geometry most accurately.

(1) $K_I = \lim_{r \to 0} \quad \sigma \cdot \sqrt{2 \cdot \pi \cdot r}$

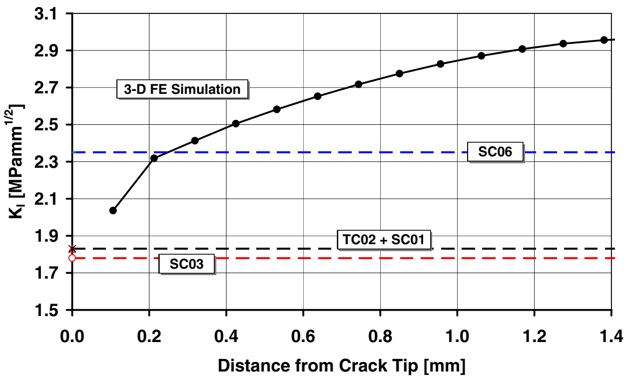

FIG. 5: K-Solution of the Different Crack Cases

The crack case SC06 significantly overestimates the stress intensity factor. However it has to be pointed out that the presented results apply only for small crack sizes. In this case a crack depth / thickness ratio (a/t) of 0.25 is investigated, based on the applied NDI limit. A further analysis with a/t ratio of 0.5 shows that the FE analysis results in considerable larger stress intensity factors compared to the one predicted by the analytical methods. This mismatch is caused by the increasing bending effect, which is strongly dependent on the geometric conditions.

The LEFM fracture mechanics concepts with analytical K-solutions have been developed as engineering procedures which are derived with respect to remote stresses of the un-cracked structure. The response of the structure with defect is predicted well as long as the crack case approximates the actual conditions, accurately.

2. CONSIDERATION OF GLOBAL OR LOCAL PLASTICITY EFFECTS IN SURFACE CRACK CONFIGURATIONS

The design of the ARIANE 5 booster cases made of 48 CrMoNiV 4 10 has been optimized during the development such that stresses close to the yield stress occur in the thin walled area during operational conditions.

LEFM no longer applies for this high stress level. Therefore a comprehensive investigation programme including fracture testing has been performed. A large number of specimens with different surface crack depths and aspect ratios (a/c) have been tested. The maximum stress intensity factor at fracture is shown in FIG. 6. The results are presented over the equivalent crack size according to equation (2), which has been chosen to eliminate crack aspect ratio (a/c) effects.

(2) $a_{equivalent} = \sqrt{a \cdot c}$

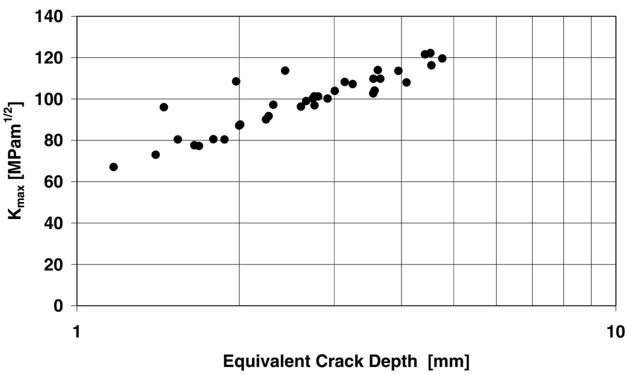

FIG. 6: Maximum Stress Intensity Factor at Fracture of the ARIANE 5 Booster Cases Steel (SCT Specimens)

It is visible that the critical stress intensity factor depends on the crack geometry. The reason is that fracture occurs at or even above yield stress, where LEFM no longer applies. Therefore failure prediction is only accurate with suitable elastic-plastic methods, where both crack tip singularity and plasticity is taken into account. This is performed with SINTAP [2], where K-solutions and collapse solutions are combined (two parameter criterion). SINTAP is similar to the R6 method [3]. Both methods are based on the failure assessment diagram (FAD) approach.

The application of SINTAP for the prediction of these SCT specimens is presented in FIG. 7. The prediction is in well agreement with test results up to 3 [mm] crack depth. With larger crack sizes the prediction becomes conservative.

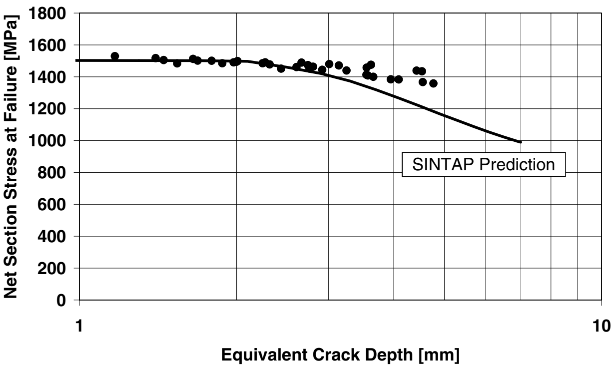

FIG. 7: Maximum Net Section Stress at Fracture of the ARIANE 5 Booster Cases Steel (SCT Specimens)

The degree of conservatism is dependent on the choice of collapse solution. In this case a most recent local solution [4] is applied which is accurate for small crack sizes. This has been successfully demonstrated for different configurations and materials [7][8][9]. A large data basis of both local and global collapse stress solutions exist in the literature (see for example [5][6]).

The skill of elastic plastic fracture mechanics is the selection of the most suitable solution, which depends mainly on

- load condition and stress triaxiality
- geometric conditions
- material behaviour (strain hardening

3. ANALYSIS OF COMPLEX STRUCTURAL CONDITIONS

In the case of the ARIANE 5 main stage tanks local stress peaks are observed in high loaded areas. One of these peaks appears at the Y-ring groove, where high bending- and high temperature gradients are superposed to high mechanical loads resulting from inner pressure and fluxes. The position of this hot spot is indicated in FIG. 8 together with the FE mesh.

The structure is made of aluminium alloy AA 2219, which shows high strength and ductility also under cryogenic conditions of main stage hydrogen and oxygen tank. For some locations the stress level due to operation and proof test conditions is close to yield stress and at some local hot spots even above.

LEFM does not apply and therefore elastic plastic methods have to be used for the damage tolerance analysis. The actual hot spot shows highly critical results even with consideration of elastic plastic methods. Therefore a 3-D FE simulation is performed for fracture assessment.

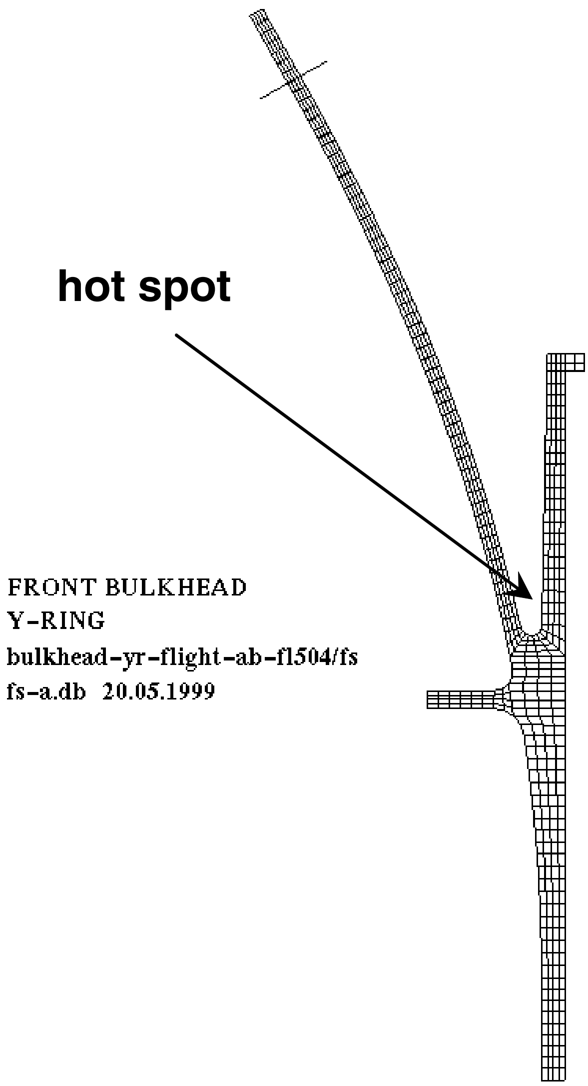

FIG. 8: Local Hot Spot in the Y-Ring of the ARIANE 5 Main Stage Tank

The 3-D FE analysis is performed with surface crack modelling of the applicable NDI limits of the series production inspection. The J-integral of the relevant structural conditions can be evaluated.

In addition damage mechanics modelling is performed using the GURSON model [10], which allows the simulation of ductile tearing. The aim of this investigation is not only to predict the crack instability but also to evaluate the crack initiation and ductile growth, which may lead to a progressive damage of the structure.

This failure mechanism is often observed for ductile materials especially when loaded up to yield stress. The method has been qualified and applied for different conditions of AA 2219 (including welds) and structural conditions [8][9].

The stress distribution over the section thickness of the hot spot is shown in FIG. 9 for the un-cracked configuration. The local peak stress at the surface is above yield stress. The opposite surface shows compression stress. A first analytical fracture analysis predicts critical crack sizes below the NDI detection limits.

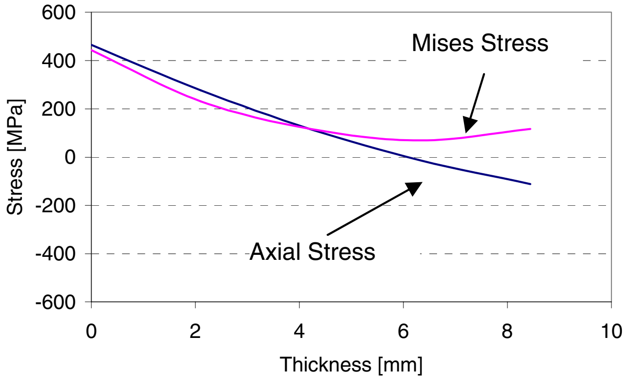

FIG. 9: Stress over Section Thickness at the Hot Spot of the Y-Ring

The results of the 3-D FE crack simulation of the structure are shown in FIG. 10. The J-integral is shown versus crack mouth opening displacement at operational stress both for the Y-ring structure and a reference simulation of a SCT specimen with identical thickness, crack geometry and applied stress over the section. The maximum J and CMOD value of the Y-ring structure is far below the crack initiation value and maximum of the SCT specimen.

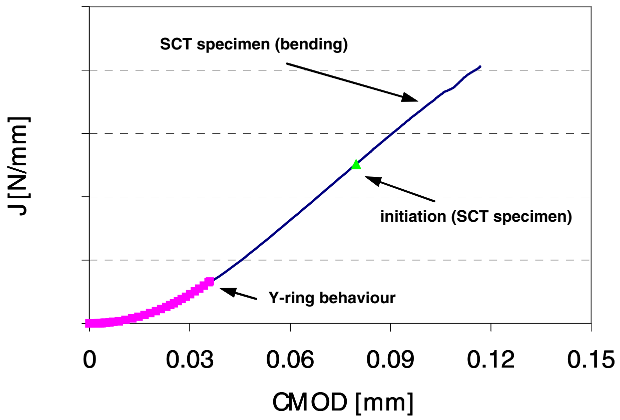

FIG. 10: J-Integral over CMOD at Operation Stress (Hot Spot of the Y-Ring)

The reason for this difference is found in the different deformation behaviour between the SCT specimen and the Y-ring. The SCT specimen geometry is used for the analytical failure prediction as no K- and collapse solution exist for the given structural geometry. In the elastic regime K is calculated only on basis of the applied load. In the non-linear regime crack tip singularity is dependent on both load and displacement.

The results clearly show that the local conditions in the Y-ring do not allow that the crack is opened to the extent which is expected at identical load level for the SCT specimen. Therefore the resulting J-integral value is much lower. The analytical prediction with SINTAP is over conservative because of inappropriate K- and collapse solutions.

The application of damage mechanics and 3-D crack simulation reveals high conservatism and allows the application of qualified NDI methods for the reliable detection of potential defects.

4. SPECIAL FEATURES OF COPV

The polar welds of a high pressure tank with composite overwrap (COPV) show plastic strain of 4 % during autofrettage. This hot spot occurs at the weld groove of the INCONEL 718 liner, caused by typical local weld imperfections in combination with local bending effects in this area. Again failure prediction with standard methods results in critical crack sizes far below the detection limits. Therefore a 3-D crack simulation is performed to predict both crack initiation and instability as presented in the section before.

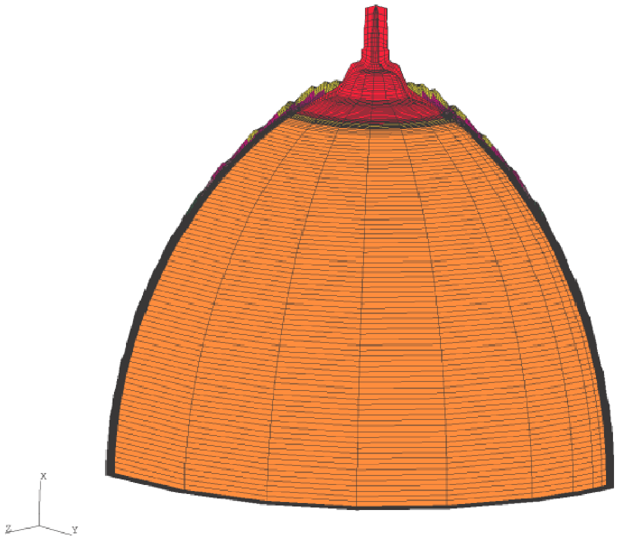

FIG. 11: FE Mesh of the COPV

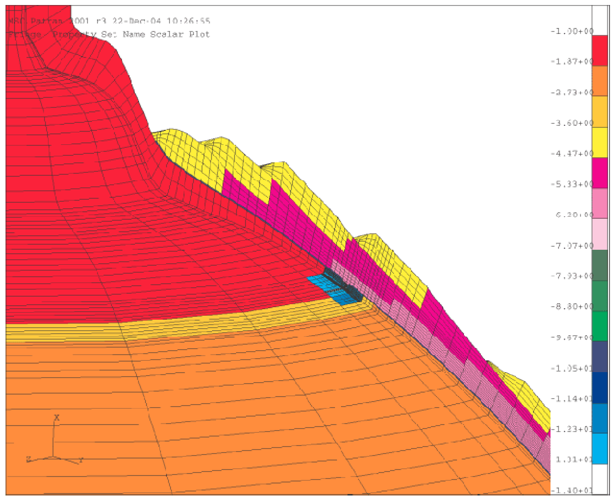

FIG. 12: FE Mesh of the COPV with local Surface Crack

A fracture test program is performed in parallel to evaluate the standard material properties as strength, σ–ε curves and fracture toughness and also the GURSON parameters for the damage mechanics simulation. A $J_{initiation}$ value of about 300 [N/mm] is evaluated with SE(B) specimens. This value is in good agreement with literature data of this alloy. The structural analyses include high plastic deformation of the liner material, orthotropic material behavior of the composite overwrap and the modeling of the bonding between liner and overwrap.

The results are shown in FIG. 13 and FIG. 14 in terms of CTOD and J-integral over tank inner pressure. The autofrettage pressure is 42.5 [bar].

The first observation is that the dependence of both parameters is linear although high plasticity occurs at autofrettage. The J-integral at autofrettage is about 80 [N/mm], which is far below the initiation value. In addition damage mechanics modeling does not predict any crack extension.

The reason of this difference compared with the analytical prediction is found in the deformation behaviour of the structure. The metallic liner is displacement (or strain) controlled by the composite overwrap, thus preventing the crack mouth opening, which can not be idealised with standard crack geometry solutions.

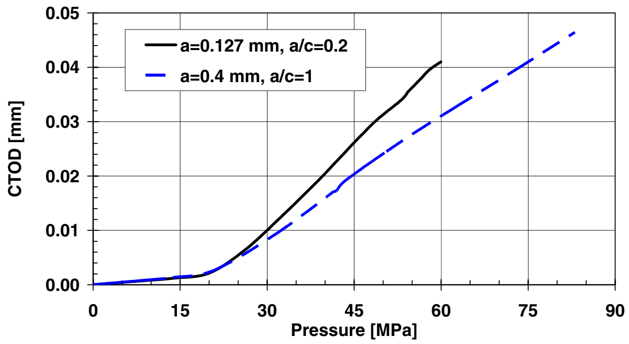

FIG. 13: CTOD Dependence from COPV Inner Pressure

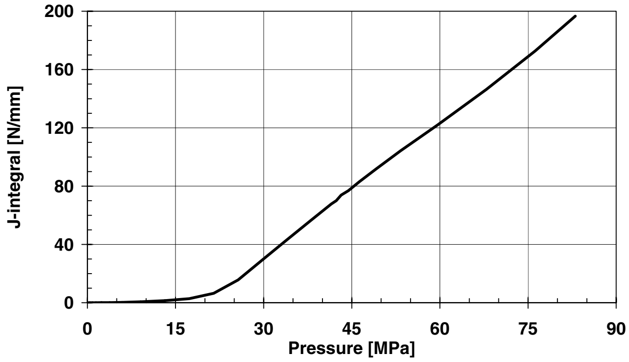

FIG. 14: J-integral Dependence from COPV Inner Pressure

5. SUMMARY

The presented examples show that fracture behaviour in structures may be more complex than predicted with simple geometry solutions.

High potential can be gained by the application of elastic plastic methods, 3-D crack simulations and damage mechanics modelling.

6. ABBREVIATIONS

a	-	Crack depth dimension
c	-	Crack length
CMOD	-	Crack Mouth Opening Displacement
COPV	-	Composite Overwrapped Pressure Vessel
CTOD	-	Crack Tip Opening Displacement
FAD	-	Failure Assessment Diagram
LEFM	-	Linear Elastic Fracture Mechanics
NDI	-	Non Destructive Inspection
SCT	-	Surface Crack Tension (Specimen)
SE(B)	-	Single Edge Bending specimen
SINTAP	-	Structural INTegrity Assessment Procedures for European Industry

7. REFERENCES

[1] ESACRACK Version 4.0, February 2000

[2] SINTAP: Structural Integrity Procedures for European Industry, British Steel, Draft Report BE95-1426 (1999)

[3] Assessment of the Integrity of Structures Containing Defects, R/H/R6-Revision 3, British Energy (1998)

[4] Sattari-Far, I. Dillström, P., Local Limit Load Solutions for Surface Cracks in Plates and Cylinders using Finite Element Analysis, Int. J. Pressure Vessels and Piping 81 (2004) 57-66

[5] Miller, AG., Review of Limit Loads of Structure Containing Defects, ", Int. J. Pressure Vessels and Piping 32 (1988) 197-372

[6] Lei Y., "J-integral and Limit Load Analysis of Semi-Elliptical Surface Cracks in Plates under combined Tension and Bending", Int. J. Pressure Vessels and Piping 81 (2004) 43-56

[7] Windisch, M., Clormann, U., Grunmach, G., Burget W. ,Sun, D-Z.: Damage Tolerance Verification Concept of the Ariane 5 Booster Welding Interface, European Conference on Spacecraft Structures, Materials and Mechanical Testing, Proceedings of the Conference held 29 November - 1 December, 2000 at ESTEC, Noordwijk, The Netherlands. Edited by C. Stavrinidis, A. Rolfo, and E. Breitbach. European Space Agency, ESASP-468, 2001., p.499

[8] Windisch, M., Eisenmann, A., Albinger, J., Varfolomeyev, I., Memhard, D. Siegele,D.: Application of Analytical (SINTAP) and Damage Mechanics Based Numerical Simulation for the Assessment of (Plastically) Hot Spots in the ARIANE 5 Main Stage Tank Bulkheads, European Conference on Spacecraft Structures, Materials & Mechanical Testing 2005, Noordwijk, The Netherlands, 10 – 12 May 2005 (ESA SP-581, August 2005)References

[9] Varfolomeyev, I., Hodulak, L., Siegele, D., Windisch, M.: Validation of the FITNET Analysis Procedure for the Assessment of ARIANE 5 Thin-Walled Components, Proceedings of FITNET 2006, International Conference on Fitness-for-Service, 17-19 May 2006, Amsterdam, The Netherlands

[10] Gurson, A. L., Continuum Theory of Ductile Rupture by Void Nucleation and Growth: Part I – Yield Criteria and Flow Rules for Porous Ductile Media, J. Eng. Mater. Technology 99 (1977) 2-15.