Use of Forming Limit Curve as a Failure Criterion in Maritime Crash Analysis

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Abstract

Calculation of the energy absorption of marine structures at certain impact scenarios by means of finite element analysis is regularly being performed by researchers. Recent studies at TNO, focusing on the vulnerability of a liquefied natural gas tank, showed that in collisions the deformation of the structures is much more complex compared to that of a simple hull (shell) structure and requires more accurate fracture criteria. In this study, forming limit diagrams (FLD) are used to identify the regions of the impacted structure that are beyond the predefined deformation limit. Via using FLD in crash analysis, compared to conventional methods, more accurate results can be obtained in a shorter post-processing time. Ls-Dyna results can easily be post processed using LS Prepost and FLD option. This paper explains why use of FLD in marine crash calculations are more accurate, and provides an example case where a gas tank is impacted by a push barge bow and FLD is used to analyze the damage.

1. Introduction

The crashworthiness of marine structures is one of the main area of interest of several parties active in maritime area. The ability of the material to absorb mechanical energy without fracture, is a very important safety feature. For offshore structures, the general approach towards a fracture criterion is based on the NORSOK standards (NORSOK Standards). For inland waterways, it is based on the ADN Guidelines (UNECE). One of the shortcomings of these guidelines is on the fracture criteria of the deformed structures. Typically a through thickness strain is used as a fracture criterion for the damaged structure. The formula used to calculate the through thickness failure strain, is based on the measurements on real deformed ship structures (GL). This method does not regard the stress states that are usually present in the deformation of more complex structures, especially cylindrical and spherical structures, and this results in for most cases a conservative conclusion. The stress states refer to different loading directions; such as uniaxial, plane strain or biaxial. In addition, knowing that nowadays different metals such as stainless steel, high tensile steel, and steels such as 460NL and 690QL are used, a fracture criterion that is valid for different materials at different thermal conditions, even at cryogenic temperatures is needed. Therefore, it is proposed to use Forming Limit Curves (FLC) for the identification of fracture at crash analysis of maritime structures. ASTM (American Society for Testing and Materials) defines FLC as “depiction of the limiting strain that a sheet metal can undergo under different forming conditions, such as deep drawing, stretching and bending before yielding” (ASTM E2218-14). As indicated with this definition, FLC was developed for sheet metal technology and nowadays used mainly in automotive industry for forming of thin metals. Use of FLC for thicker steels is being investigated (Alsos, Hopperstad and Tornqvist).

FLC is generally obtained performing series of experiments and documenting the principal strains to necking (or fracture). Different specimen geometries are typically needed to create a curve that covers a large range of stress states (triaxialities) (Allwood and Shouler). Nakazima test (Nakazima, Kikuma and Asaku) is a common method to obtain the forming limit curve of metals. It is based on the punching technique and visually assessing the strain localization and documenting the maximum strain before yielding. These strain values indicate the upper limit of a safe zone.

There are several analytical approaches to calculate FLC as summarized by Chung et al. (Chung, Kim and Lee). Recent studies are focusing on developing analytical methods that can predict the curve with an input from a single uniaxial test (Voormeeren, Walters and Tang). However, these theories that are based on a single experimental input are not validated experimentally. In the current study presented in this paper the focus is on the use of the curve for crash analysis. Therefore a simplistic analytical approach is followed for the formation of the FLC which is based on assumptions that are explained further in the paper.

In this paper, first the conventional method of finding failure strains at crash analysis is described and the shortcomings of this method are highlighted. Next, how to develop FLC for different metals and its use in crash analysis are explained. This is followed by an example of analysis of a cylindrical tank impacted by a push barge bow via use of FLC. Finally in conclusion pros and cons of using FLC in crash analysis are summarized.

2. Conventional method of finding failure strains at crash analysis

A typical way of identification of failure of a structure that is undergoing a significant deformation due to impact is observing the thickness reduction of the impacted surface and pinpointing the moment that the thickness reduction is at the limit of the allowed strain of the given material at given initial thickness. For metals, usually the metal certification documents provide the maximum elongation that the material can undergo under uniaxial deformation. This provided failure strain, ε_f, can be translated to the through thickness strain, ε_t, by the following relation (Eq. (1)):

$$\varepsilon_t = \frac{\varepsilon_f}{1 + \varepsilon_f} \qquad (1)$$

The use of this relationship is based on the condition that the plate is constrained in the transverse direction and the total volume remains constant. The failure strain given in the material certification usually is based on uniaxial tensile tests. In order to take into account the element dimensions and thicknesses, equation (2) has been developed and used commonly (GL). Equation (2) is known as the GL criterion and assumes that the elements used in finite element model are square.

$$\varepsilon_f(l_e) = \varepsilon_g + \varepsilon_e \frac{t}{l_e} \qquad (2)$$

where:
ε_g = structural uniform strain
ε_e = necking strain
t = element thickness
l_e = element edge length

Using equation (2) failure strain that is provided with the material certificates can be adjusted for the specific thickness of the modelled structure and the length of the elements used in the simulation. Normally, uniform and necking strain, ε_g and ε_e respectively, depend on the stress vs. strain relation of the metal. For typical shipbuilding steel (mild steel) based on real accidents the necking and uniform strains were measured and determined as following values (BV):

ε_g = 0.056
ε_e = 0.54

The measured structure, in this case the ship side structure, is typically stretched at plane strain condition, where the transverse strain is constrained. This means that the values are only valid for the plane strain type stress state. For other stress states such as biaxial and uniaxial loading, other relations should be developed. Also, the materials that have different stress vs. strain behavior compared to mild steel, or mild steel at different temperatures will have different necking and uniform strains. These issues can be resolved by use of forming limit curves that are developed specifically for the material used in the structure.

3. Use of FLC for crash analysis

A typical FLC looks like the dark line shown in Figure 1. In this figure the principal strains are plotted on the x and y axes. When used in an FEM analysis, principal strains of elements are plotted on this diagram. If they stay below the curve, the elements are safe, and if above they are failed. The region highlighted with the shaded grey is the compression region (wrinkling). In this region the thickness of elements increase, and for crash analysis this region is considered to be safe. This typical curve shows that at plane strain type of stress state (the minor strain is 0) the major strain is the lowest within all the stress states. This charts shows that the difference of maximum strain capacity of metals at different triaxialities can change significantly.

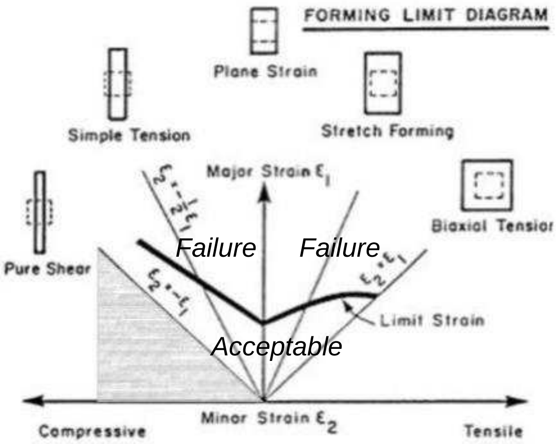

Figure 1 A typical forming limit curve (PVLT)

Developing a forming limit curve based on uniaxial data

For this study, a simplified method for the forming limit curve based on the available material and structure data is developed and used. Since principal strains are plotted in an FLC, a relationship between the fracture strain and principal strains are needed. Von misses strains, or effective strains, ε_{eff} in terms of principal strains $(\varepsilon_1, \varepsilon_2, \varepsilon_3)$ are described as follows;

$$\varepsilon_{eff} = \frac{\sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2}}{\sqrt{2}(1 + \upsilon)} \qquad (3)$$

Metals are isochoric, meaning that the volume of the material is unchanged by plastic flow, which corresponds to a Poisson's ratio, υ of 0.5.

$$\varepsilon_{eff} = \frac{\sqrt{2}}{3}\sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_1 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_2)^2} \qquad (4)$$

Assuming conservation of volume (removing higher order terms) during deformation:

$$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0 \qquad (5)$$
$$\varepsilon_3 = -(\varepsilon_1 + \varepsilon_2) \qquad (6)$$

Placing eq. (6) in eq. (4) gives us eq. (7)

$$\varepsilon_{eff} = \frac{2}{\sqrt{3}}\sqrt{({\varepsilon_1}^2 + {\varepsilon_2}^2 + \varepsilon_1\varepsilon_2)} \qquad (7)$$

Simple tension $\varepsilon_2 = -\frac{1}{2}\varepsilon_1$ (8)

Plane strain $\varepsilon_2 = 0$ (9)

Placing eq. (8) in eq. (7) gives for simple tension:

$$\varepsilon_{eff} = \frac{2}{\sqrt{3}}\sqrt{({\varepsilon_1}^2 + \frac{{\varepsilon_1}^2}{4} - \frac{{\varepsilon_1}^2}{2})} \quad (10)$$

$$\varepsilon_{eff} = \frac{2}{\sqrt{3}}\sqrt{\frac{3{\varepsilon_1}^2}{4}} = \varepsilon_1 \quad (11)$$

Placing eq. (9) in eq. (7) gives for plane strain:

$$\varepsilon_{eff} = \frac{2}{\sqrt{3}}\sqrt{({\varepsilon_1}^2)} = \frac{2\varepsilon_1}{\sqrt{3}} \rightarrow \varepsilon_1 = \frac{\sqrt{3}}{2}\,\varepsilon_{eff} \quad (12)$$

Based on this information a forming limit curve can be predicted assuming;

1. Left hand side of the curve is linear,
2. Right hand side is horizontal,
3. Failure plastic strain is equal to effective plastic strain at simple tension and plane strain ($\varepsilon_{eff} = \varepsilon_{failure}$)

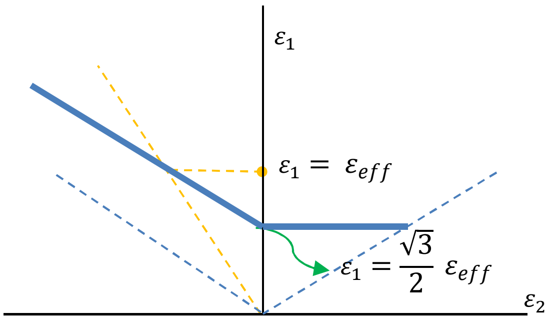

Figure 2 Forming limit curve and fracture strain relation assumed for this study

Gage length correction

The fracture strains or minimum guaranteed elongations given at material certificates are values for certain gage lengths. While using fracture strains in FE analysis, these values should be corrected for the element length used in the model. In a uniaxial test, initially the gage region deforms uniformly until yielding starts at a local necking area. As the deformation progresses, the local neck region keeps stretching. Assuming that the neck length stays same as the deformation progresses, a formula to calculate the fracture strain for the thickness and element length of the model can be developed as explained further.

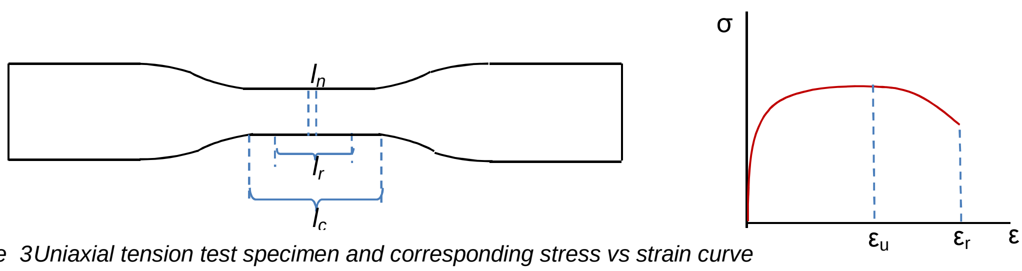

Figure 3Uniaxial tension test specimen and corresponding stress vs strain curve

l_n, necking length
l_r, reference length, the length used in the experiment or given in the certificate
l_c, calculated length, the length of the element in the FEM
ε_n, necking strain
ε_r, reference strain, the strain given as result of experiment or in the certificate
ε_c, calculated strain, the fracture strain of the element in the FEM
ε_u, uniform strain, can be obtained from the material stress-strain curve

The elongation of the reference length is the summation of the elongation at the necking region and the rest:

$$\Delta l_r = \Delta(l_r - l_n) + \Delta l_n \quad (13)$$

$$\varepsilon = \frac{\Delta l}{l} \rightarrow \Delta l = \varepsilon l \quad (14)$$

$$\varepsilon_r l_r = \varepsilon_u (l_r - l_n) + \varepsilon_n l_n \quad (15)$$

Assuming that the necking length stays the same for different gage lengths:

$$\varepsilon_c l_c = \varepsilon_u (l_c - l_n) + \varepsilon_n l_n \quad (16)$$

Subtracting eq. (16) from eq. (15);

$$\varepsilon_c l_c = \varepsilon_r l_r - \varepsilon_u l_r + \varepsilon_u l_c \quad (17)$$

$$\varepsilon_c = \frac{\varepsilon_r l_r - \varepsilon_u (l_r - l_c)}{l_c} \quad (18)$$

4. Case study: Gas tank impacted by a push barge bow

Implementation of FLC at crash analysis via LS Prepost is used in this case study. The forming limit curve developed experimentally or theoretically for the relevant material and the thickness of the section should be read using the FLD button. Selecting the formability option from the drop down menu opens a box and highlights the regions in different colors indicating their position relative to the limit curve. If the energy absorption up to the failure of the structure is required, FLC can be used to indicate the instance of the severe stretching of the structure and the energy absorption up to this instance can be obtained by summing the internal and sliding energies.

The procedure for crash analysis involves crash simulations of the vessel with push barge bow impactor moving at 10 m/s impact velocity, at mid height of the tank. The FE model is shown in Figure 4. The tank length is 33 m, diameter is 4.6 m. The tank supports (shown in light brown in Figure 4) is 20 mm thick and 2.5 m wide. The tank ends are 20 mm thick. Rest of the tank shell is 14 mm thick. The model is meshed with shell elements (not shown in the figure) that are approximately 100 x 100 mm. The crash calculations are made with the explicit finite element program LS-DYNA. In the calculation the impactor is assumed rigid. The tank initial pressure is 6 bar. In LS-DYNA the pressure in the tank is modelled with the keyword '*AIRBAG_SIMPLE_PRESSURE_VOLUME'.

At support 1 (Figure 4), the tank is free to move in longitudinal direction, at support 2 all directions are constrained. The tank body is made of high tensile steel (HTS) with a yield stress of 690 MPa (S690) and a failure strain of 14%. The tank ends are made from steel with a yield stress of 460 MPa (S460) and a failure strain of 17%. These values are given by Bureau Veritas (BV) as the minimum guaranteed failure strains that is measured for certain gage length, L_o.

$$L_o = 5.65\sqrt{S_o} \quad (19)$$

where S_o is the cross section area = t * b, t is the thickness of the test specimen, and b is the width of the specimen and prescribed in Bureau Veritas as 25 mm. The material thickness and element size of the model should be taken into account with the gage length correction to calculate the fracture strains that is valid for the model.

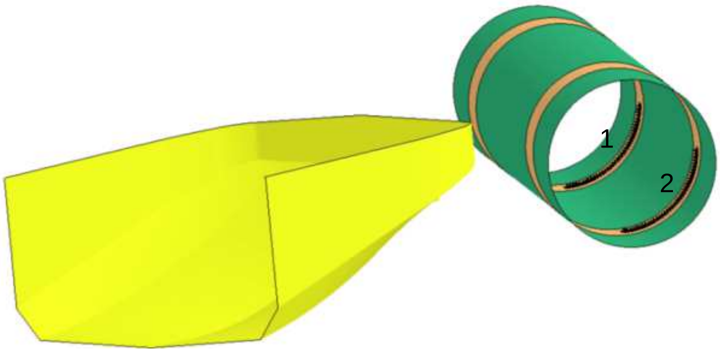

Figure 4 A tank impacted with a push barge bow, constraints highlighted (tank ends removed for better visualisation)

For the current investigation three FLCs are proposed; FLC for HTS 690QL (tank shell 14 mm thickness, tank stool region 20 mm), which is used for tank shell, 460NL which is used for tank end. Therefore, a forming limit diagram based on fracture strains is recommended to be used for the tank. The following section explains how fracture strain was calculated and how to form a forming limit curve for the current crash analysis.

Fracture strain for the tank shell of 14 mm thick 690QL steel

Using equation (19) gage length for 14 mm thick 690QL is calculated as

$$5.65\sqrt{25 * 14} = 106\ mm \qquad (20)$$

This means that the minimum guaranteed elongation given by (BV) is valid for a gage length of 106 mm. Since 100 mm elements are used in the model, a small correction is needed. For this correction eq. (18) is used. Uniform strain that is needed for this conversion can be predicted using the material curve given in Figure 5. In this figure the fracture strain of 690QL is given as 17% and the uniform strain (strain at where the necking starts) is given as 6%. (BV) provides 14% for the fracture strain of this material. Using the ratio of fracture to uniform strain from the material curve, the uniform strain can be calculated as:

$$\frac{\varepsilon_{u\ curve}}{\varepsilon_{f\ curve}} = \frac{6\%}{17\%} = 0.35 \qquad (21)$$

Assuming that the same relation between uniform and fracture strain is valid:

$$\frac{\varepsilon_{u\ BV}}{\varepsilon_{f\ BV}} = 0.35 \rightarrow \varepsilon_{u\ BV} = 0.35 * \varepsilon_{f\ BV} = 0.35 * 14 = 4.9\% \qquad (22)$$

Placing in eq. (18)

$$\varepsilon_c = \frac{\varepsilon_r l_r - \varepsilon_u (l_r - l_c)}{l_c} = \frac{14 * 106 - 4.9(106 - 100)}{100} = 14.55\% \qquad (23)$$

Fracture strain for the tank end of 20 mm thick 460NL steel

Gage length for 20 mm thick 460NL is calculated as:

$$5.65\sqrt{25 * 20} = 126\ mm \qquad (24)$$

Following eq. (18) fracture strain for 100 x 100 element size can be calculated. Uniform strain is needed and can be predicted using the material curve given in Figure 5. In this figure the fracture strain of 460NL is given as 24% and uniform strain (strain at where the necking starts) is given as 15%. BV gives 17% for fracture strain. Using the ratio of fracture to uniform strain from the material curve, the uniform strain can be calculated as:

$$\frac{\varepsilon_{u\ curve}}{\varepsilon_{f\ curve}} = \frac{15\%}{24\%} = 0.62 \quad (25)$$

Assuming that the same relation between uniform and fracture strain is valid:

$$\frac{\varepsilon_{u\ BV}}{\varepsilon_{f\ BV}} = 0.62 \rightarrow \varepsilon_{u\ BV} = 0.62 * \varepsilon_{f\ BV} = 0.62 * 17 = 10.5\% \quad (26)$$

Placing in eq. (18)

$$\varepsilon_c = \frac{\varepsilon_r l_r - \varepsilon_u (l_r - l_c)}{l_c} = \frac{17 * 126 - 10.5(126 - 100)}{100} = 18.7\% \quad (27)$$

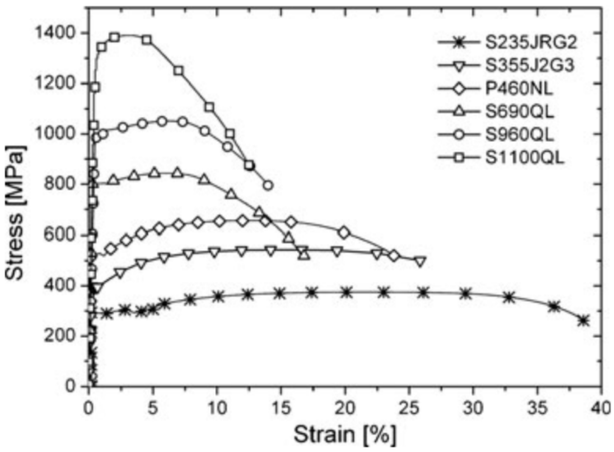

Figure 5 Material curves based on tensile tests for different type of steels (Farajian)

Using the relationship developed earlier and the fracture strains obtained using the gage length correction, the data points for the forming limit curves for different sections of the tank are listed in Table 1 and plotted as shown in Figure 6. Each line corresponds to a material and thickness combination which refer to different regions on the tank. In this figure, the dashed line on the left hand side show the compression region. Below this curve, the elements are in compression and not expected to rupture (wrinkling region). The region below the biaxial line is not a physical region since the definition of the major principal strain refers to the largest of the principal strain values. Please note that assuming horizontal line on the right hand side is not accurate, however for this case study the deformation of the tank is not in this region (as shown further in the paper), and horizontal line is a conservative assumption.

Table 1 Principal strain values for the tank

	Tank End		Tank Stool		Tank Shell	
	18.70		16.40		14.55	
	e1	e2	e1	e2	e1	e2
Uniaxial	18.70	-9.35	16.40	-8.20	14.55	-7.28
Plane str	16.19	0.00	14.20	0.00	12.60	0.00
Biaxial	16.19	16.19	14.20	14.20	12.60	12.60

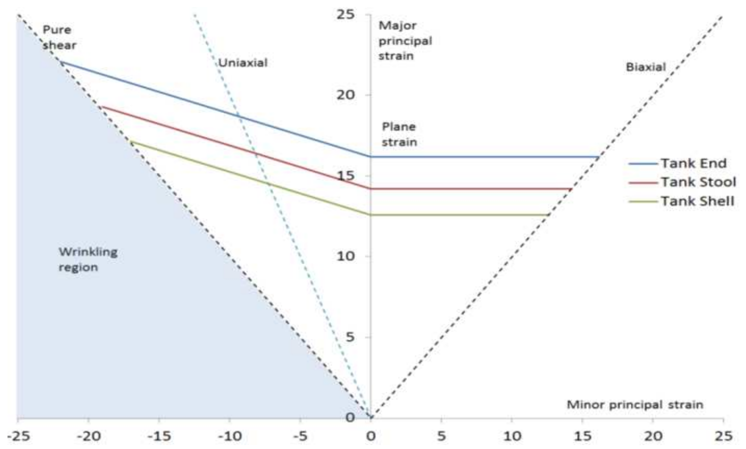

Figure 6 The forming limit curves based on the uniaxial fracture strain

5. Results

Figure 7 a) shows the tank impacted with a push barge bow at the middle, highlighting the safe (green) and failed elements (red). In this case, a safety margin of 25% is selected and the yellow elements are showing the elements that fall in this region. Purple elements fall in the wrinkling region where the element thickness increases. At the same time, the respective positions of elements can be plotted on a forming limit diagram as shown in Figure 7 b). This representation also indicates the stress state of the deformed elements. Figure 8 shows the tank impacted at the tank end. In this case, corresponding FLC is different (as calculated earlier and shown in Figure 6). As shown in these figures, it is very convenient to visualize the deformation of a complex geometry with a FLC using LS Prepost. As it can be seen in these FLDs, the deformation in these simulations are at the central location (for the tank shell impact) and left hand side (for the tank end impact) of the diagram. Therefore, it can be said that assumption of considering a horizontal line on the right hand side is acceptable for this case study. Please note that the conventional method of using GL criterion in failure analysis that is based on plane strain condition is conservative for the tank ends where the deformed elements do not fall in the plane strain region (comparison of Figure 7 b) and Figure 8 b)).

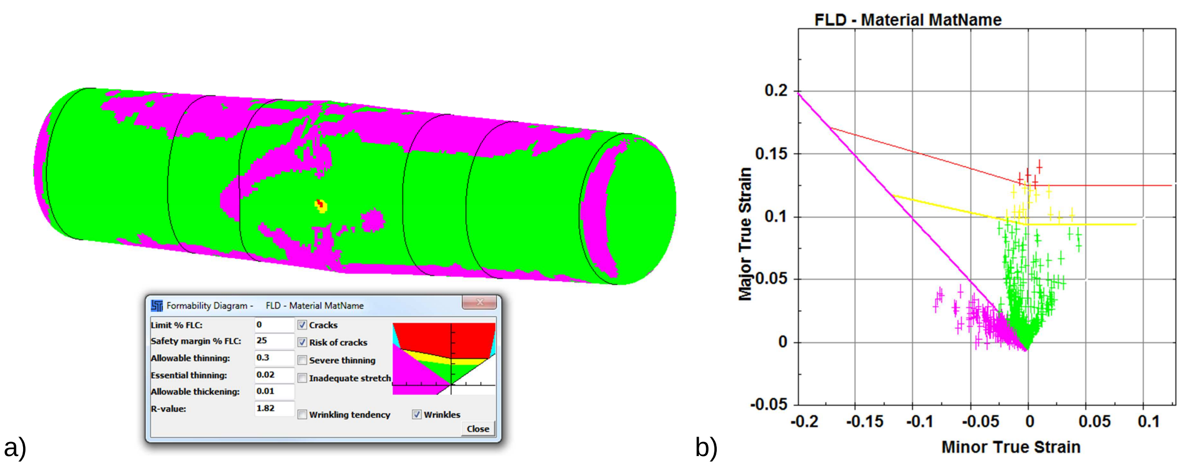

Figure 7 Forming limit diagram is shown on an example case – Tank impacted at the middle.

a) b)

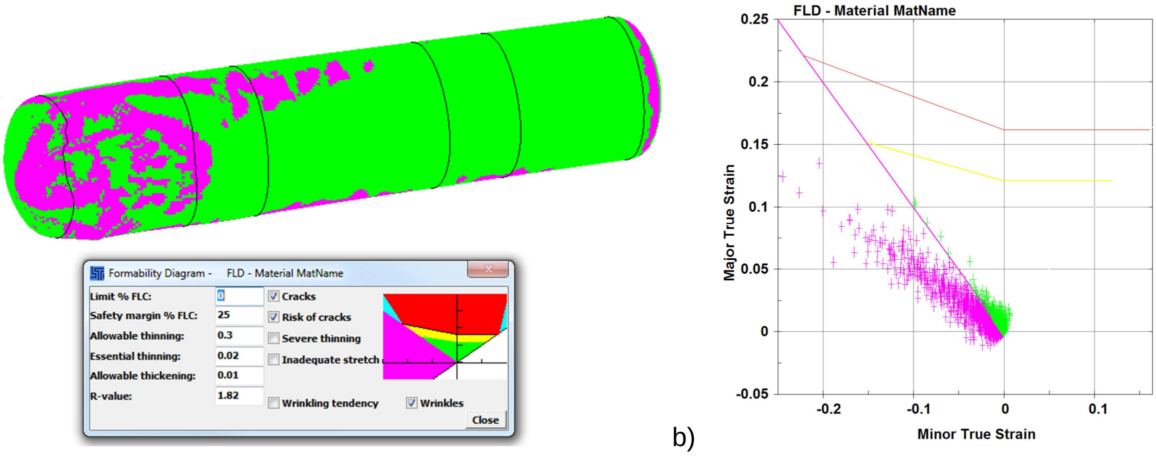

Figure 8 Forming limit diagram is shown on an example case – Tank impacted at the tank end

In addition to a tank analysis, other studies focusing on a crash onto a ship side shell (results not shown here), it is observed that the stress state is generally in the plane strain region. For such structure GL criteria and FLC provide similar results. However, for complex structures, especially for spherical geometries, use of FLC is recommended.

6. Conclusions

The conventional method for failure analysis involves reviewing the through thickness strain with respect to the failure strain. Usually the GL criterion, that is based on damaged ship structures failed at plane strain condition, is used where the failure strain is corrected taking into account the size of the elements in the analysis and the thickness of the structure. However, a gage length correction is generally not performed. In this paper, a simple gage length correction method is proposed based on the uniaxial stress vs. strain curve.

For the visualization of the failed elements, including the structures made of thick metals such as tanks, it is proposed to use forming limit curves. By using LS Prepost, it is very convenient to highlight the regions where the elements are stretched beyond the predefined limits, as well as the elements that are in compression. Plotting the forming limit diagram for the selected elements or a part shows the stress state of elements. Especially for the tank ends it is shown that the deformation falls further from the plane strain region, where the allowable strain is typically greater than the plane strain deformation. Therefore, it can be concluded that the conventional method of using GL criterion is conservative for the spherical structures, as shown in the deformation of the tank ends.

Accurate prediction of failure in crash analysis of complex structures using FLC highly depends on a correctly defined curve. There are numerous analytical methods for calculating FLC, based on different variables. Experimental methods for developing FLC are also used for thin metals. In literature, experimental methods for thick metals are also mentioned.

This paper showed that the use of FLC in crash analysis of complex structures performed in LS Dyna can easily be implemented using LS Prepost, but accuracy depends on the input of a correct curve.

7. Works Cited

Allwood, J.M and D.R. Shouler. "Generalized forming limit diagrams showing increased forming limits non-planar stress states." Int. Journal of Plasticity (2009): 1207-1230.

Alsos, H.S., et al. "Analytical and numerical analysis of sheet metal instability using a stress based criterion." Int. Journal of Solids and Structures, 45 (2008): pp. 2042-2055.

ArcelorMittal. Forming. n.d. 23 April 2015 <http://automotive.arcelormittal.com/europe/products/AHSS/TRIP/EN>.

ASTM E2218-14. Standard Test Method for Determining Forming Limit Curves. West Conshohocken, PA: ASTM International, 2014.

BV. “Rules on Materials and Welding for the Classification of Marine Units.” NR216. 2011.

Chung, K., H. Kim and C. Lee. “Forming limit criterion for ductile anisotropic sheets as a material property and its deformation part sensitivity. Part 1.” Int. Journal of Plasticity (2014): 58.

Farajian, Majid. “Welding residual stress behavior under mechanical loading.” International Institute of Welding (2013).

GL. Abschlussbericht zum Vorhaben MTK0614, Kollisionsberechnungen in schiffbaulichen Entwurfssystemen. GL Document. Bonn: Germanischer Lloyd, 2002.

LS-Dyna. http://www.dynasupport.com/tutorial/computational-plasticity/the-equations-for-isotropic-von-mises-plasticity. n.d.

Nakazima, K., T. Kikuma and K. Asaku. “Study on the formability of steel sheet.” Yawata Technical Report. 1968.

NORSOK Standards. “N-004, Design of steel structures.” 2004.

PVLT. Forming limit curve prediction. 31 May 2011. 23 April 2015 <http://www2.warwick.ac.uk/fac/sci/wmg/research/pvlt/simulation/bodystructure/flc/>.

Siemerink B.V. Design Calculations for Liquified Pressurised Gas Tanks. REference 5891. Geertruidenberg, 07-03-2014.

UNECE. “European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways.” http://www.unece.org/fileadmin/DAM/trans/danger/publi/adn/adn2013/English/English_Vol_1.pdf. 2013.

Voormeeren, L.O, et al. “Estimation of Failure Parameters for Finite Element Simulations Based on a Single State of Stress and Arbitrary Stress-Strain Relation.” ASME2014 33rd Int. Conf. on Ocean and Arctic Engineering. San Francisco, 2014.