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PROPOSAL FOR AMENDMENTS TO ANNEXES A AND B OF ADR

Adequate Equivalence Minimum
Wall Thickness Formula

ADR marginal 21x 127 (3) and (4)

Transmitted by the Government of Germany

Foreword

1. The matter had been discussed during several sessions of the Working Party (WP.15), workings groups and Ad hoc working groups and the summary of the discussions was given by Germany during the 66th session of WP.15. Because of different interests of the participants or the various meetings no final agreement could be reached up to now. Therefore, Germany announced during the 66th session to submit a formal proposal on the matter for the 67th session to ask for a final discussion leading to a decision to change the present marginal 21x 127 (3) and (4) into the following wording and to add some consequential amendments.

Proposal

2. Replace each of the last sentences of Marginals

211 127 (3)
211 127 (4)
212 127 (3)
212 127 (4)

by the following text:

"Equivalent thickness" means the thickness obtained by the following formula:

$$e_1 = \frac{456 \cdot e_0}{\sqrt[3]{(Rm_1 \cdot A_1)^2}}$$ 4/

3. Replace footnote 4/ concerning the above mentioned marginals as follows:

4/ This formula is derived from the general formula:

$$e_1 = e_0 \cdot \sqrt[3]{\left(\frac{R_{m0} \cdot A_0}{R_{m1} \cdot A_1}\right)^2}$$ _

where

R_{m0} = 360

A_0 = 27 for the reference mild steel

R_{m1} = minimum tensile strength of the metal chosen, in N/mm^2; and

A_1 = minimum elongation of the metal chosen on fracture under tensile stress, in %

4. Marginals 211 125 (1) and 21 125 (1), consequential amendment

Add the following sentence to the fourth paragraph of the above mentioned marginals (starting with: "When austenitic steels are used....")

These specified minimum values shall not be exceeded when using the formulas in marginal 211 127 (3) and (4) [212 127 (3) and (4)].

5. Marginal 211 188, consequential amendment

Reword marginal 211 188 as follows:

Fixed tanks (tank vehicles), demountable tanks and battery vehicles constructed before the entry into force of the provisions applicable from [1 January 2001] which do not conform to those provisions but were constructed according to the requirements of ADR in force until that date may still be used.

6. Marginal 212 182, consequential amendment:

Reword marginal 212 182 as follows:

Tank-containers constructed before the entry into force of the provisions applicable from [1 January 2001] which do not conform to those provisions but were constructed according to the requirements of ADR in force until that date may still be used.

Justification

7. Introduction

The main kind of stresses on tanks respectively shells during accidents involve locally and globally caused stresses. Where stresses are created locally by aggressively shaped parts, the failure limit is determined by the strength parameters of the material on one hand and by the deformation abilities of the material on the other hand, if deformations are not restricted by design i.e. Where stresses are caused globally, failure mainly occurs where differences in stiffness (e.g. tank ends, internal or external reinforcement rings or welded reinforcement belts) impede deformation or if deformation leads to a decrease of volume respectively an increase of pressure. In brief, failure limits are depending on the kind of load affecting the shell.

Accident evaluations and tests performed show that the present “equivalence or cubic root formula” for determining wall thicknesses of tanks having material characteristics different to those of mild steel does not lead to tank designs with equivalent safety levels.
Details can be taken from document TRANS/WP.15/R. 433 in connection with INF.32 (62nd session of the WP.15). So, the WP.15 at its 64th session agreed that in principle the insufficient minimum thicknesses for shells in road transport were the consequences of the inadequacy of the present cubic roof formula of marginal 21x 127 (3) and (4) of ADR in determining these thicknesses. Therefore a small ad hoc Working Group was looking for solutions to replace the present cubic root formula to ensure equivalent safety levels of tank walls made of different metallic materials referring to basic safety levels given by tank walls made of reference mild steel having wall thicknesses of 4 respectively 6 mm. Additional boundary conditions should not be applied.

So, primarily the accidental behaviour of the membrane-like parts and the structural ability of a tank should be taken into account.

During the 66th session of the WP.15 Germany gave a report concerning all the efforts of the ad hoc Working Group (see INF.13)

8. Possible solutions

8.1 Load related solutions

Loads to be taken into account are

- penetration (shearing),
- bending moments,
- overall (structural) impact.

Tanks made of different metallic materials should be able to withstand besides service stresses the same amount of accidental stresses (penetration loads, bending moments and overall impact input) to ensure the same safety level for each different tank, in principle. So, each kind of shell must be able to bear the necessary amount of shearing force, bending moment and deformation work (energy absorption capacity) up to its failure limits.

The transformation from one material to another concerning the ability of the shell to withstand the same amount of shearing force has to be done by applying the new formula in tables 1 and 2. For the transformation concerning bending moments the supplementary formula 2 in tables 1 and 2 has to be chosen. The transformation from one material to another concerning the same amount of deformation by penetration up to the failure limit of the shell respectively of overall impact input has to be done by applying supplementary formula 1 in tables 1 and 2. Details can be taken from document TRANS/WP.15/R.433 and INF. 32.

Each kind of load leads to different wall thicknesses.

To cover all kind of loads for shells made of different materials the highest calculated figure should be chosen.

For the reason of instability problems like stiffness, buckling a.s.o. additionally the settlement of minimum wall thicknesses may be necessary (see German comments on the Spanish document TRANS/WP.15/1999/13)

Solution No. 1:

In a first step, a load related solution to change the present inadequate cubic root formula into an adequate equivalence wall thickness requirement could be worded as follows:

For materials weaker than mild steel, solutions based on supplementary formula 1 should be taken. For materials stronger than mild steel solutions based on the new formula respectively on the supplementary formula 2 should be taken.

Conclusion:

Shells made of aluminium-alloys will become thicker if compared with wall-thicknesses being necessary up to now. Besides, the application and evaluation of three different load-related formulas seems to be complicated and not error-resistant enough.

8.2 Development of an alternative equivalent wall thickness formula

The application of only one formula out of three related to the load leading to the maximum figure concerning equivalent wall thickness seems not to be sufficient under some aspects:

If penetration occurs by stressing the membrane-like parts of a shell e.g., deformation will not be limited up to the failure limits of the shell being described by supplementary formula 1. But, if penetration of the tank shell occurs nearby a welding joint, stiffening ring or lateral reinforcement, the deformation is limited, so, bending moments or shearing forces have to be taken into account, primarily, and the new formula or the supplementary formula 2 have to be applied. In brief, the same kind and amount of load will lead to different stresses, depending on the location the load will be applied to the tank shell.

Solution No. 2:

It is reasonable to stipulate an average load being composed of the three different loads, which are the basis for the new formula and the supplementary formulas 1 and 2 (covering sustainable shearing forces, bending moments and deformation work), respectively, it will be sufficient to stipulate an average minimum wall thickness being composed of the wall thicknesses, which are calculated by applying the new formula and the supplementary formulas 1 and 2.

Examples for the calculation of average thicknesses can be found in tables 1 and 2, also.

This would be a satisfying and correct solution, but like Solution No. 1 application of this method is not error-resistant and its verification is difficult to do.

Solution No. 3:

A comprehensive substitute for Solution No. 2 can be derived from the standardised stress-strain-test (uniaxial tensile test) requirements. The result of this derivation can be found as the alternative formula in tables 1 and 2. Details of the derivation are shown in part 3. Calculations by applying the different load related formulas and the alternative formulas (using properties of different metallic materials like shown in table 3) are leading to the result that Solution No. 2 (average minimum wall thickness) is in very good accordance with Solution No. 3 (alternative formula). So, the alternative formula can be applied as a real accidental-load-related formula and it should replace the present cubic root formula given in marginal 21x 127 (3) and (4) to different metallic materials, ensuring the required safety level.

Like said before the application of Solution No. 3 is based on the uniaxial tensile test. The main advantages of the tensile test are:

- it is standardised world wide,
- it is easy to verify,
- therefore, Solution No. 3 (alternative formula) is easy to be verified, too.

By applying the alternative formula the properties of austenitic steels concerning accidental loads are evaluated in a correct and sufficient manner, so the special requirement for austenitic steels in marginal 21x 125 (1) (specified minimum values may be exceeded up to

15 %) is invalid for its application in marginals 21x 127 (3) and (4).

Application of Solution No. 3 may result in very small wall thickness for certain metallic materials. So, additional limitations concerning minimum wall thicknesses will be necessary to avoid instability problems like buckling e.g. In the meantime Spain had submitted a proposal on the subject (see document TRANS/WP.15/1999/13). Therefore no separate additional proposal is needed within this document; German comments on the Spanish paper will be submitted separately.

9. Derivation of the alternative formula

If for tensile testing a short proportional specimen is taken, the permanent elongation after fracture shall be measured on a specimen (test piece) of circular cross-section in which the gauge length l is five times the diameter d; if test pieces of rectangular section are used - which is completely normal for determining the properties of sheet metal - the gauge length shall be calculated by the formula

$$l = 5{,}65 \cdot \sqrt{F_0} \qquad (1),$$

where F_0 is the initial cross-sectional area of the test piece (see also marginal 21x 125, footnote 1).

The volume V of the cylindrical and the prismatic specimen should be equal. Therefore (see fig. 1)

$$V = \frac{\pi}{4} d^2 \cdot l = F_0 \cdot l = b \cdot e \cdot l \qquad (2)$$

and $d = \sqrt{\frac{4}{\pi}} \cdot \sqrt{b \cdot e}$

where $l = 5 \cdot d$, resulting in

$$l = 5 \cdot \sqrt{\frac{4}{\pi}} \cdot \sqrt{b \cdot e} = 5{,}65 \cdot \sqrt{b \cdot e} \qquad (3)$$

The deformation properties of the specimen (deformation work resp. energy absorption capacity) can be described as follows:

$$\Delta W = V \cdot \int_0^{\varepsilon} \sigma d\varepsilon \qquad (4)$$

If the metal has ideal elastic-plastic properties (see fig. 2) equation (4) can be transformed into

$$W = V \bullet R_m \bullet A \qquad (5)$$

where

V = Volume of the specimen

R_m = tensile strength

A = Elongation on fracture under tensile stress

If another metal will be chosen which shall be able to absorb the same amount of deformation work like the basic metal equation (5) has to be transformed as follows:

$$W = V \cdot R_m \cdot A = \text{const.}$$

$$W = V_0 \cdot R_{m0} \cdot A_0 = V_1 \cdot R_{m1} \cdot A_1 \qquad (6)$$

where

Index 0 = metal (steel) of reference,

Index 1 = metal chosen.

In a next step equations (2) and (3) will be introduced in equation (6) like follows:

$$W = R_{m0} \cdot A_0 \cdot V_0 = R_{m1} \cdot A_1 \cdot V_1$$

$$= R_{m0} \cdot A_0 \cdot b_0 \cdot e_0 \cdot 5{,}65 \cdot \sqrt{b_0 \cdot e_0} \qquad = R_{m1} \cdot A_1 \cdot b_1 \cdot e_1 \cdot 5{,}65 \cdot \sqrt{b_1 \cdot e_1}$$

where $b_0 = b_1$ = const. (like it is for real tank shells of a given diameter e.g.), so the following result will be reached:

$$R_{m0} \cdot A_0 \cdot \sqrt{e_0^{\,3}} = R_{m1} \cdot A_1 \cdot \sqrt{e_1^{\,3}}$$

$$\sqrt{e_1^{\,3}} = \sqrt{e_0^{\,3}}\ \frac{R_{m0} \cdot A_0}{R_{m1} \cdot A_1}$$

$$e_1^{\,3} = e_0^{\,3} \left(\frac{R_{m0} \cdot A_0}{R_{m1} \cdot A_1} \right)^2$$

$$e_1 = e_0 \sqrt[3]{\left(\frac{R_{m0} \cdot A_0}{R_{m1} \cdot A_1} \right)^2} \qquad (7)$$

So, the derivation of the alternative formula is complete.

10. Final remark

Although metals do not show ideal elastic-plastic behaviour, really, nevertheless the application of equation (5) is quite correct, because the area ratio (area under a realistic stress strain-curve (F_1) divided by the area under the ideal elastic-plastic curve (F_0)) for each metal shows nearly always the same amount (0.89 to 0.91). So, within a range of up to 2 or 3 % the results of the transformation of wall thicknesses following the alternative formula (equation 7) show negligible deviations to realistic area ratios. By the way, this remark has to be made concerning the application of the present cubic root formula, too.

Formula	Material	Reference mild steel	Al Mg 4,5 Mn	Austenitic steel (1.4541)	Fine grained steel (St E 460)
Cubic Root Formula	$e_1 = e_0 \sqrt[3]{\frac{R_{m0} \cdot A_0}{R_{m1} \cdot A_1}}$	6,0	7,7	4,5 (4,3)	6,1
New Formula	$e_1 = e_{11} = e_0 \cdot \frac{R_{m0}}{R_{m1}}$	6,0	7,9	4,0	3,9
Supplementary Formula 1	$e_1 = e_{12} = e_0 \cdot \frac{R_{m0} \cdot A_0}{R_{m1} \cdot A_1}$	6,0	12,5	2,5	6,1
Supplementary Formula 2	$e_1 = e_{13} = e_0 \cdot \sqrt{\frac{R_{m0} \cdot A_0}{R_{m1} \cdot A_1}}$	6,0	8,7	3,9	6,1
Average Figure (Solution No. 2)	$e_1 = \frac{\sum_{i=1}^{3} e_{1i}}{3}$	6,0	9,7	3,5	5,4
Alternative Formula (Solution No. 3)	$e_1 = e_0 \sqrt[3]{\left(\frac{R_{m0} \cdot A_0}{R_{m1} \cdot A_1}\right)^2}$	6,0	9,8	3,4	6,1

Table 1: Required Wall thickness e_1 [mm] with e_0 = 6 mm in reference mild steel (R_{m0} = 360 N/mm² and A_0 = 27 %) depending on tank material

Formula	Material	Reference mild steel	Al Mg 4,5 Mn	Austenitic steel (1.4541)	Fine grained steel (St E 460)
Cubic Root Formula	$e_1 = e_0 \sqrt[3]{\frac{R_{m0} \cdot A_0}{R_{m1} \cdot A_1}}$	4,0	5,12	3,0 (2,9)	4,0
New Formula	$e_1 = e_{11} = e_0 \cdot \frac{R_{m0}}{R_{m1}}$	4,0	5,2	2,7	2,6
Supplementary Formula 1	$e_1 = e_{12} = e_0 \cdot \frac{R_{m0} \cdot A_0}{R_{m1} \cdot A_1}$	4,0	8,3	1,7	4,1
Supplementary Formula 2	$e_1 = e_{13} = e_0 \cdot \sqrt{\frac{R_{m0} \cdot A_0}{R_{m1} \cdot A_1}}$	4,0	5,8	2,6	4,1
Average Figure (Solution No. 2)	$e_1 = \frac{\sum_{i=1}^{3} e_{1i}}{3}$	4,0	6,4	2,3	3,6
Alternative Formula (Solution No. 3)	$e_1 = e_0 \sqrt[3]{\left(\frac{R_{m0} \cdot A_0}{R_{m1} \cdot A_1}\right)^2}$	4,0	6,5	2,2	4,1

Table 2: Required Wall thickness e_1 [mm] with e_0 = 4 mm in reference mild steel (R_{m0} = 360 N/mm² and A_0 = 27 %) depending on tank material

Property / Material	Reference mild steel	Al Mg 4,5 Mn	Austenitic steel (1.4541)	Fine grained steel (St E 460)
R_{m0} [N/mm²]	360	-	-	-
A_0 [%]	27	-	-	-
R_{m1} [N/mm²]	-	275	540	560
A_1 [%]	-	17	43	17
$R_{m0} \bullet A_0$	9720	-	-	-
$R_{m1} \bullet A_1$ $((R_{m1} \cdot A_1) + 15\,\%)$	-	4675	23220 (26700)	9520

Table 3: Material properties of frequently used tank materials

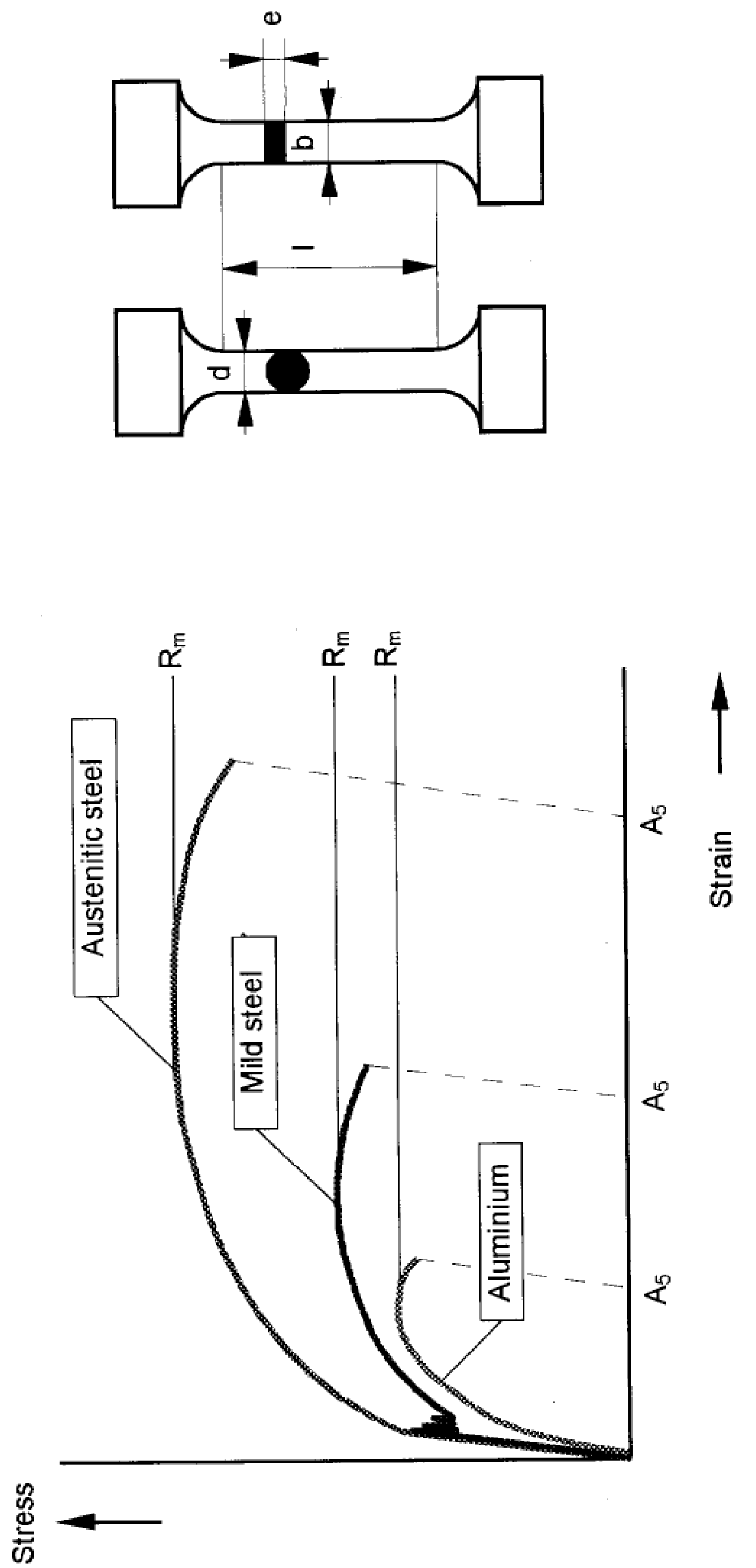
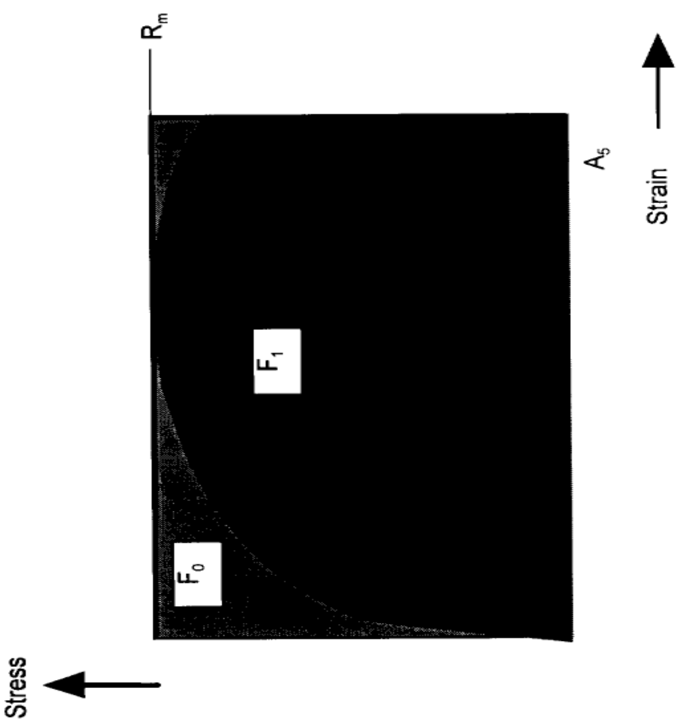


Figure 1: Stress - strain diagram of typical tank materials (diagrammatic view)



Area F_0: Deformation work (Ideal elastic-plastic behaviour)
Area F_1: Deformation work (Realistic stress-strain-curve)

Figure 2: Ideal and realistic stress-strain-curves (diagrammatic view)