TALAT Lectures 2712

Design Example in Fatigue Based on European Standard ENV 1999-2 (Eurocode 9)

14 pages, 3 figures

Advanced Level

Prepared by Dimitris Kosteas, Technische Universität München, Germany

Update from the TAS Project :

TAS alu

Leonardo da Vinci program
Training in Aluminium Alloy Structural Design

Date of Issue: 1999

ABSTRACT AND REMARKS

The text of the European Standard ENV 1999 (version as of April 1997) should be available, as the calculation example is based on these rules. Explanations to the rules, accompanying the actual fatigue check procedure, have been integrated into the overall format, but are written in italics. This is a fully documented calculation example with direct reference to the actual code provisions. Its purpose is to present an outline of necessary steps but also of possible considerations for other cases or possibilities of enhancement of fatigue behaviour in service.

We draw attention to the fact that since a National Application Document proposal has been produced for the ENV 1999-2 which may be adopted on a national level and possibly at later date introduced into the actual standard, when this is converted from an ENV to an EN, the information given in the Supplement to the TAS / TALAT Chapter 2400 Update should be taken into consideration. Changes in the adopted S-N design lines and consideration of the new document EN 30042 on the quality and detail classification criteria are the main issues here. Regarding the first point numerical changes in the design example calculations will emerge, but the overall concept and the procedure of the design life check is not affected. Regarding the detail classification a simpler procedure is presented by EN 30042 than the current provisions in the ENV 1999-2. But it should also be noted that in practice we still lack the necessary information for a reliable and quantifiable correlation between the structural detail classification schemes and fatigue service behavior of these details. This is also reflected in the lack of harmonization between various national or international structural detail classifications, especially harmonization in the respective critical imperfection values used for characterization of the different classes. In this context see: Kosteas, D., Bompard, S., Mugnier, P., „Correlating Design and Quality Requirements of Welded Aluminium Structural Details in Fatigue“, IIW Doc. No. XIII-1589-95.

Previsions as in Eurocode 9	**2711 Design Example in Fatigue** Based on European Standard ENV 1999-2 (Eurocode 9)

Contents

1 Introductory Remarks

1.1.1(1)

Eurocode 9, Part 2 gives the basis for the design of aluminium alloy structures with respect to the limit state of fatigue induced fracture. Other limits states to be checked as well, *as covered in Part 1.*

1.1.1(2)
2.1.6
1.1.1(3) *For the structural case given below the safe life design method shall be applied, i.e. the* fatigue check will be performed on the basis of an appropriate S-N design line. Quality requirements have to be met too, *to ensure that the design assumptions are met in practice.*

2 Description of Structural Detail and Service Conditions

1.1.3(3)
1.1.4, 1.1.5, Table 1.1.1
1.1.6, 1.2
1.1.7
1.4

The structural part under consideration is an extruded square, hollow tube with 160/160 mm side size and a wall thickness of 8 mm in alloy EN AW-6082. It has an attachment of 8 mm thickness welded to one edge over a length of 300 mm. There is an additional opening in the vicinity of the attachment. The tube forms the chord of a latticed structure, Fig. 1, and is under axial variable loading, exposed to normal atmospheric conditions. Quality of workmanship is assumed as defined in the code (more below under 1.12).

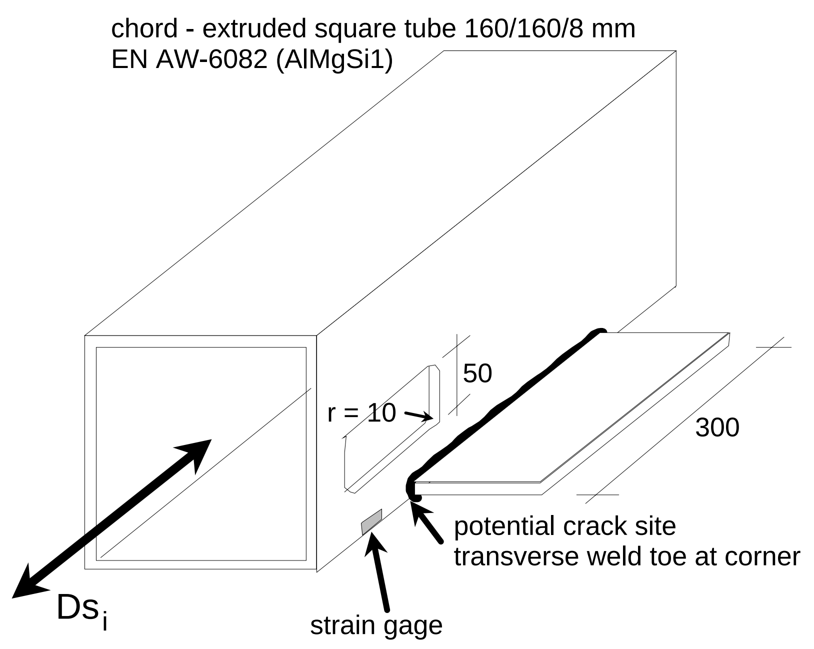

Figure 1: Structural Component

2.1 *The code gives valuable information on design objectives, influence of fatigue to design, potential sites and mechanisms of failure, and fatigue susceptibility which form a background for sound workmanship.*

3 The Design Procedure

Certain prerequisites have to be met:

2.2.1 – *service history (loading sequence and frequency), stress response*
(1) *history at potential failure sites to be checked, shall be available,*
– *fatigue strength characteristics of the potential sites shall be available in terms of respective fatigue design curves,*
(2) – *quality standards in the manufacture of the component containing potential failure sites shall be defined.*
(3)

4 Loading and Stress Spectrum

2.2.2 (2) a) *Obtain an upper bound estimate of the service loading sequence for the*
3.1 (1) *structure's design life. All sources of fluctuating stress are observed,*
(2) *the* loading being given by the relevant loading standard (often ENV
3.2 (1) 1991 Eurocode 1) *and loading or stress expressed in terms of the design load spectrum.* In the case under consideration continuous strain
3.2(3) gage measurements over a suitable sampling period - chosen as one month - were conducted. *These one-month measurements were*
Annex C.1 *repeated for a number of times. The* results are given in Table 1, *second column. The estimated intensity of the design load spectrum - Table 1, fourth column - is based on the mean measured value plus k_F=2 standard deviations.*

3.2 (5)

Table 1: Stress Spectrum					
	measurement		service life		
stress level	cycles n_i or n_j	Σn_i	cycles n_i or n_j	Σn_i	stress range $\Delta\sigma_i$ in N/mm²
i = 1	7	*7*	5040	*5040*	60
2	25	*32*	18000	*23040*	40
3	31	*63*	22320	*45360*	36
4	53	*116*	38160	*83520*	32
5	72	*188*	51840	*135360*	28
6	111	*299*	79920	*215280*	24
7	194	*493*	139680	*354960*	20
8	445	*938*	320400	*675360*	16
„knee point" of design line at N_D = 5000000 with constant amplitude fatigue limit $\Delta\sigma_D$ = 15 N/mm²					
j = 9	1445	*2383*	1040400	*1715760*	12
10	(2056)	*(4439)*	(1480320)	*(3196080)*	(8)
11	(3556)	*(7995)*	(2560320)	*(5756400)*	(4)

The number of cycles given here as the result of the one-month measurement corresponds actually to the mean observed number of cycles plus k_N=2 standard deviations. Under these conditions the partial safety factor for loading γ_{Ff} is assumed equal to 1 *and provides an acceptable level of safety. The* assumed service life is equal to T_L =

3.4(1)
Table 3.4.1

60 years = 720 months*, the respective cycle numbers are given in the fourth column of Table 1.*

2.2.2 (2) b)
4.2.1, 4.3.1
4.3.4
4.4.1 (1) and (2) !
4.2.2
2.2.2 (2) c)
Annex A, A.4
Fig. A.2.1

The resulting stress at the potential crack initiation site, the beginning or end of the attachment weldment, has been derived, as mentioned above, by strain gage measurements in direction of the chord axis. The latter were used in this case for the purpose of continuous representative recording of the stress sequence. So they had to be placed in sufficient distance from the actual beginning or end of the weldment, in order to record nominal stresses. Care should be given to this fact, i.e. not to record hot spot stresses, which are then compared to the inappropriate design curve of the code. Since the stresses were derived from measurements in the vicinity of the potential crack site, *there is no need to apply any further stress concentration factor because of the opening on the side of the tube. Had the nominal stresses been derived on the other hand by static analysis of the structural member only, an appropriate stress enhancement should have to be considered. The stress concentration factor would have been in this case between 1,00 and 2,55 - but the exact value may have to be calculated by finite element analysis for instance.*

2.2.2 (2) d)
4.5.1(1) + (2)
4.5.2
2.2.2 (2) e)

The originally recorded stress sequence and history have been reduced to an equivalent number n_i *of cycles of different stress ranges* $\Delta\sigma_i$ *(usually using a cycle counting method - appropriately the reservoir method as in the existing case of rather simple loading events).Since only a limited number (11) of different stress range values have been recorded, there is no need of further groupings of the initial bands of the spectrum. But, of course, in a certain sense this grouping has taken place when we extrapolated from the cycle numbers of the one-month measurement to the total assumed service life of* T_L *= 720 months.* The spectrum is set up in descending order of stress range values, Table 1.

5 Structural Detail Classification and S-N Curve Parameters

2.2.2 (2) f)
5.1.1
5.1.2

The next step is the categorisation of the potential crack initiation detail, i.e. the welded longitudinal attachment. Taking into account all factors affecting the fatigue strength of the structural detail we proceed to the appropriate detail category table*. Although the attachment is a longitudinal one in the direction of the applied stress, the potential crack initiation detail is the weld toe, this being transverse to the applied stresses.*

Table 5.1.2 (a)

So we have to consult Table 5.1.2 (a)„Members with Welded Attachments - Transverse Weld Toe“. *The initiation site under consideration is found (caution !) not under reference no. 3 in the table but under reference no. 2, which describes the „transverse weld toe on stressed member at corner“. We check the further assumptions:*

– *stress orientation is normal to transverse weld toe,*

– *the alloy type is irrelevant with weldments,*
– *the attachment is on the member surface,*
– *the weld is, practically, round the corner (assumption on the safe side),*
– *the length of the weldment/attachment is 300 mm (>200 mm),*
– *after fabrication the undercut should be ground smooth,*
– *inspection, testing and quality standards have to be observed as Annex D,*
– *the stress parameter is the nominal stress at initiation site (see above),*
– *the weld profile permitted is given in Annex D,*
– *the stiffening effect of the attachment is already accounted for.*

Annex D Table D1 and D2

Thus we arrive to the detail type number 2.9 from Table 5.1.2 (a) *and for the thickness of T=8 mm (4<T<10 mm) we get the characteristic parameters of the appropriate S-N design line:*

$\Delta\sigma_c$ = 20 N/mm² *(from 22 N/mm² according to type no. 2.8 but reduced by one detail category for 2.9 to account for the fact that the weld toe is round the corner of the member)*

m_1 = 3,2 *for the slope*

The respective design line can thus be constructed, Fig. 2.

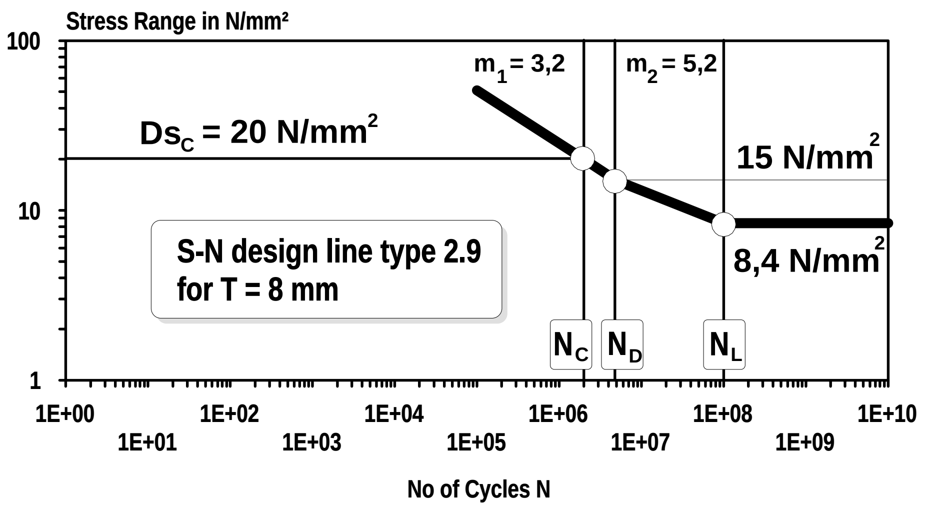

Figure 2: Structural Detail Category and Design Line

6 Fatigue Damage and/or Life Check

Table 2: Computation of Damage						
m	i	Ds_i N/mm²	n_i	N_i	n_i / N_i	$\sum (n_i / N_i)$
3,2	1	60	5040	59462	0,0848	0,0848
	2	40	18000	217638	0,0827	0,1675
	3	36	22320	304900	0,0732	0,2407
	4	32	38160	444474	0,0859	0,3266
	5	28	51840	681428	0,0761	0,4027
	6	24	79920	1115964	0,0716	0,4743
	7	20	139680	2000000	0,0698	0,5441
	8	16	320400	4084530	0,0784	0,6225
„knee point“ of design line at N_D = 5000000 with constant amplitude fatigue limit Ds_D = 15 N/mm²						
5,2	9	12	1040400	28486789	0,0365	**D_L = 0,6590**
cut-off limit Ds_L = 8,4 N/mm²						
	10	(8)	(1480320)	---------	---------	
	11	(4)	(2560320)	---------	---------	

The fatigue check on the basis of total damage D_L is performed by means of Miner’s summation (linear damage accumulation)

2.2.2 (2) g) $$D_L = \sum (n_i / N_i) = 0{,}659$$

following the algorithm as shown in Table 2. *This already indicates that there is a „safety margin“ against failure D_L = 1,0. Of course, only as far as the assumption of linear damage accumulation holds and no significant stress sequence effects (crack rate acceleration) prevail.*

Finally the code defines also „safe life“ T_S, *which may be calculated as*

$$T_S = T_L / D_L = 60 / 0{,}695 = 86{,}3 \text{ years.}$$

Had the damage summation been D_L > 1,0 or the „safe life“ T_S shorter

2.2.2 (2) h) *than the assumed or projected service life T_L, then*

- *either the structure or the member will have to be redesigned (or protected in case of exposure to severe environment) to reduce*

2.2.2 (2) i) *stresses, or*

- *a detail of higher category will be manufactured, if possible, or*
- *a damage tolerant approach may be used, where appropriate.*

2.3

7 Fatigue Check of „Damage Equivalent Stress“ (alternatively)

Somewhat larger number of calculations is required, but nowadays using computational methods for the algorithm this is not at all a matter of concern. Such a calculation has the advantage of comparing stress instead of life values, with the other limit states as well. The procedure is as follows:
the „damage equivalent stress“ $\Delta\sigma_e$ is calculated for the stress spectrum at a total spectrum life of 675360+1040400 = 1715760 cycles (corresponding to the „active“ stress amplitudes above the cut-off limit, but it would have been the same if the equivalent stress had been calculated at any other life value), where with the values as in Table 3 *we get*

Table 3: Fatigue Strength Check on the Basis of „Damage Equivalent Strength“

m	i j	$\Delta\sigma$	n_i n_j	$\sum n_i$ $\sum n_j$	$n_i \Delta\sigma_i^m$ $n_j \Delta\sigma_j^m$	$\sum n_i \Delta\sigma_i^m$ $\sum n_j \Delta\sigma_j^m$	$\Delta\sigma_D^{m_1 - m_2}$
	1	60	5040	5040	2,469E09	2,469E09	
	2	40	18000	23040	2,409E09	4,878E09	0,00444...
	3	36	22320	45360	2,132E09	7,010E09	
	4	32	38160	83520	2,501E09	9,511E09	
3,2	5	28	51840	135360	2,216E09	11,727E09	
	6	24	79920	215280	2,086E09	13,813E09	
	7	20	139680	354960	2,034E09	15,847E09	
	8	16	320400	675360	2,285E09	18,132E09	
„knee point“ of design line at N_D = 5000000 with constant amplitude fatigue limit $\Delta\sigma_D$ = 15 N/mm²							
5,2	9	12	1040400	1040400	425,5E09	425,5E09	
cut-off limit $\Delta\sigma_L$ = 8,4 N/mm²							
	10	(8)	(1480320)	--------	--------	--------	
	11	(4)	(2560320)	--------	--------	--------	

$$\Delta\sigma_e = \sqrt[m_1]{\frac{\sum\left(n_i \Delta\sigma_i^{m_1}\right) + \Delta\sigma_D^{m_1 - m_2} \cdot \sum\left(n_j \Delta\sigma_j^{m_2}\right)}{\sum n_i + \sum n_j}}$$

$$= \sqrt[3,2]{\frac{18{,}132E09 + 0{,}00444 * 425{,}5E09}{675360 + 1040400}}$$

$$\cong 18{,}7 \; N / mm^2$$

The fatigue strength $\Delta\sigma_R$, as given by the design line at the same life value as above, i.e. for N = 1715760 cycles, is

$$\Delta\sigma_R = \Delta\sigma_C \left(\frac{N}{N_C}\right)^{-\frac{1}{m_1}} = 20\left(\frac{1{,}715760E06}{2{,}0E06}\right)^{-\frac{1}{3{,}2}} = 20 \cdot 1{,}0491$$

$= 20{,}98$ N/mm²

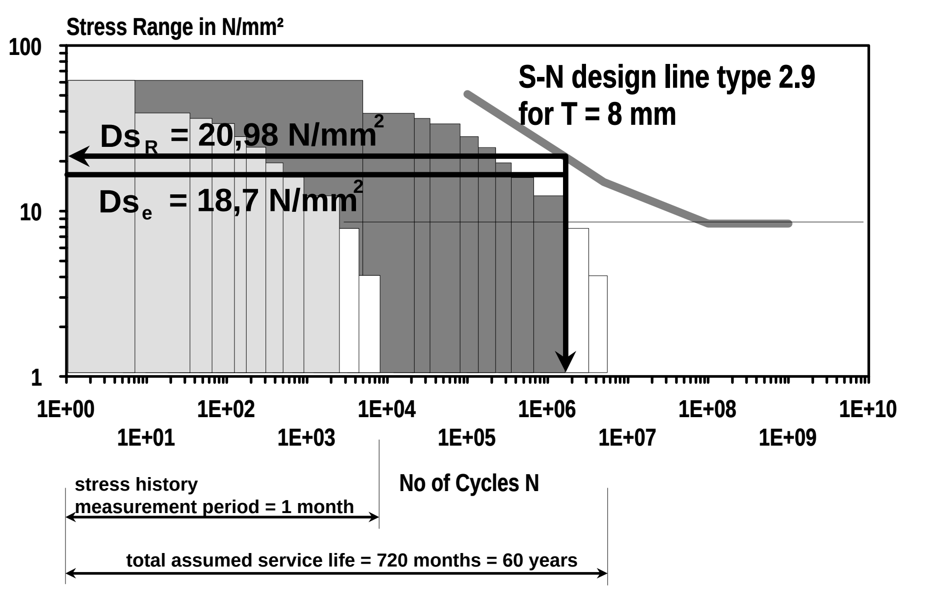

Figure 3: Damage Equivalent Stress

Since Ds_e < Ds_R there exists a margin of safety in stress of approximately 1,12.

By the way, as a verification of the correctness of our calculations or the fact that the two fatigue check methods are identical, consider that according to the definition of the design line $N = C \cdot \Delta\sigma^{-m}$ *it must be*

$$\frac{\log N_1}{\log N_2} = \frac{\Delta\sigma_1^{-m}}{\Delta\sigma_2^{-m}} = \left(\frac{\Delta\sigma_2}{\Delta\sigma_1}\right)^m \quad \text{with } N_1 > N_2 \text{ and } \Delta\sigma_2 > \Delta\sigma_1$$

which is equal to

$$\frac{1}{D_L} = \left(\frac{\Delta\sigma_R}{\Delta\sigma_e}\right)^m$$

$$\frac{1}{0{,}695} \qquad \left(\frac{20{,}98}{18{,}7}\right)^{3{,}2}$$

$$1{,}44 \qquad 1{,}12^{3{,}2}$$

$$1{,}44 \equiv 1{,}44 \quad \text{q.e.d.}$$

In other words the margin of safety in stress of 1,12 corresponds to a margin of safety in life of 1,44.

8 Conditions for Damage Tolerant Design Calculations

2.3.1 *Conditions under which damage tolerable design procedures may be used*

- $D_L > 1{,}0$
- *crack propagation observable during service (crack near or at surface) or crack arrest,*
- *inspection frequency feasible before critical crack size,*
- *practical crack inspection methods available and applicable before critical crack size is reached,*
- *maintenance manual to be kept.*

2.3.2 *First inspection has to take place*

- *before safe life* T_S *has elapsed,*
- *at regular inspection intervals* $T_i \le 0{,}5T_f$ *, where* T_f *is the calculated time for a crack to grow (at the site being assessed) from the detectable crack size* l_d *to critical crack size* l_f*.*

Table 2.3.1 *Minimum safe values of detectable surface crack length are given by the Code.* T_f *shall be estimated by means of calculation (based on fracture mechanics principles and an upper bound crack propagation /*
Annex B *stress intensity relationship) and/or by test. Specific information is*
Table C.1 *provided in this latter case, too.*

9 Comments for the Mean Stress Effect

During the fatigue check we have assumed conditions of high tensile mean stresses at the potential crack initiation site of the weld toe. This is generally true. Conditions of mean stress ≥ +0,5 are taken into account (as worst case, on the safe side) with the design S-N lines.
5.3, Annex G *Should other conditions pertain fatigue life may be enhanced - accounted for by a „bonus“ factor f(R).*

10 Comments on Environmental Effects

The fatigue check performed above showed a sufficient margin of safety under the assumed conditions of loading and environmental conditions (see under 1.1) for detail category used. Under another, more severe environment, for instance immersion or constant contact
5.4 *with sea water with the alloy EN AW-6082 (AlMgSi), a reduction of*
Table 5.4.1 *two detail categories should have been undertaken. This would result to a design line with* $Ds_C = 16$ *N/mm² and slope* $m_1 = 3{,}2$*. The constant amplitude fatigue limit (at* $5x10^6$ *cycles) would now be* $Ds_D = 12$ *N/mm², the cut-off limit (at* 10^8 *cycles)* $Ds_L = 6{,}8$ *N/mm². These changes would alter the damage accumulation calculation, more stress levels would have to be considered at more severe damage. The structural detail category would not be sufficient any more under these conditions.*

11 Enhancement of Fatigue Strength

The practical remedy would be to improve the structural detail, either locally at the potential crack initiation site (this can be a costly
5.5 *procedure, its applicability will depend on the overall frequency of occurrence of the detail in the structure and the economics of the improvement technique applied) or choose a detail of higher strength*
Table *in the first place. The obvious solution in this case would have been an*
5.1.2 (a) *attachment with a sufficiently high radius R ≥ 20 mm and the weld toe fully ground out. This would push the detail category up to type no. 2.12 with Ds_C = 28 N/mm². Now even after reducing by two categories due to the severe environmental conditions there would be a category with Ds_C = 22 N/mm², sufficient to provide sound design.*

12 Quality Requirements for the Structural Detail Used

Reference has already been made above (under 1.1) to the fact that the detail categories used represent the maximum fatigue strength
Annex D permitted by this code for the detail in question when manufactured to
Annex C the quality requirements specified in the Code, and shall not be exceeded without further substantiation by test. *See below under 1.14 for details concerning inspection and workmanship acceptance levels. Higher class details often require additional inspection and demand higher workmanship standards which can have an adverse effect on the economy of manufacture.*

13 The Fitness-for-Purpose Concept

It is important to realize that Eurocode 9 introduces a new concept:
6.1 (1)-(2) inspection and workmanship standards shall be determined by the quality level appropriate to the particular fatigue performance requirements and not by the maximum potential fatigue resistance. The
6.1 (3) required quality level at a detail shall be obtained by determining the
Table 6.1.1 lowest fatigue strength curve for which Miner's summation D_L does not exceed unity. Caution: where stress fluctuations occur in more than one direction at a detail different class requirements may be found for each direction.

In the above initially calculated case the detail category 2.9 with Ds_C
Table 6.1.1 *= 20 N/mm² would correspond itself already to a „Normal" required quality level. Of course this would be true for any lower category for which D_L would still be ≥ 1,0. Should we have used though a detail with rounded attachment edges (and under normal environmental conditions) of say type 2.12 or even 2.13, then a detail category of Ds_C = 31 N/mm² would have resulted. Following the argumentation just mentioned and from the point of view of the „required quality level" this high level would not be required, a „Normal" level would have been sufficient. In case that this detail with the higher potential fatigue resistance would have been chosen it means that quality requirements*

6.2.1 (b)

resistance would have been chosen it means that quality requirements on manufacture of this detail could be relaxed (or in other words larger imperfections may be tolerated). In case that the required quality level exceeds „Normal“, i.e. it is higher than Category 20, the required quality level has to be indicated on the drawings together with
the direction of stress fluctuation.

14 Inspection and Workmanship Acceptance Levels

Coming back to the inspection and workmanship acceptance levels, for instance for our initial detail type no. 2.9 from Table 5.1.2 (a), the transverse weld toe at corner, we may observe the following. The Code gives rather detailed instructions for the control of welding quality and methods and extent of inspection.

Annex D
D.1.2, D.1.3

Table D.1

The methods and extent of inspection for production welds are as follows:

- *Stage 1 - immediately prior to welding / visual and dimensional inspection (all weld or joint types, for all orientations) in 100% of joints of surface condition, preparation and fit-up dimensions, jigging and tacking requirements,*
- *Stage 2 - after completion of welding / visual and dimensional inspection 100% as above,*
- *Stage 3 - after visual inspection / non-destructive testing for a) surface discontinuities and b) sub-surface discontinuities and for a butt or fillet transverse, in „Normal“ required quality level, a penetrant dye test for 100% of joints within 20 mm of a stop or start is prescribed,*
- *it is obvious that for „Normal“ required quality level no additional destructive tests are prescribed.*

Table D.2

The required quality levels for final acceptance of production welds and any corrective actions are also indicated. These recommendations help avoid unnecessary repair. Again for our case of detail type no. 2.9 from Table 5.1.2 (a), the transverse weld toe at corner, we observe the following acceptance criteria in the case of „Normal“ required quality level:

whereby D: dimension specified on drawing/ E: corrective action-refer to designer
NP: not permitted (for NDT detectable discontinuities)
NL: no limit
NA: not normally applicable

see dimensions indicated in weldments Fig. D.2.1

<u>overall weld geometry</u> - referring to location $D \pm 10$ / *E*
weld type D / E
extent (length) $D+10-0$ / *E*
<u>profile discontinuities</u> - actual throat thickness $a \geq D$
(average over 50 mm) $a \leq D + 5$
leg length - (average over 50 mm) $z \geq D$
toe angle - transverse weld $\theta \geq 90°$

linear misalignment - longitudinal $h \leq D + 0{,}4t$ *(t: plate thickness)*
<u>*surface breaking discontinuities*</u> *- undercut - Longl* $h_1 + h_2 \leq 0{,}1t$
lack of root penetration - Longl $h \leq D + 0{,}01t$ *(average 50 mm)*
porosity - Longl $d \leq 2$ *and* $\sum d \leq 20$
(summation over 100 mm length)
lack of fusion $l \leq NP$
cracks $l \leq NP$
<u>*sub-surface discontinuities*</u>
lack of fusion root penetration $h \leq 3$
Longl - full depth $h' \leq 6$; $\sum l \leq 3t$
(summation over 100 mm weld length)
$l \leq NL$
$l' \geq NL$
$h' > 6$ $l \leq NL$
$l' \geq NL$
root gap - partial penetration butt $h \leq 3$
copper inclusion *NA*
solid and other inclusions $d \leq NA$
porosity $d \leq NA$
cracks *NP*

15 References

1. ENV 1999-2/Eurocode 9: Design of aluminium structures - Structures susceptible to fatigue.

2. ENV 1999-1/Eurocode 9: Design of aluminium structures - General rules - General rules and rules for buildings.

3. ENV 1991/Eurocode 1: Basis of design and actions on structures.

4. Kosteas, D.: Fatigue and Fracture. A compact course in english. Technische Universität München. Summer Semester 1997 (not published).

5. Kosteas, D.: Betriebsverhalten und Bemessung von Aluminiumkonstruktionen. In: Stahlbau-Handbuch, Band 1, Teil B, S. 411-543. Stahlbau-Verlagsgesellschaft mbH, Köln, 1996. (With further literature also on the area of fatigue).

6. TAS - Training in Aluminium Alloy Structural Design - WP1. ASD: Aluminium Structural Design, Part 2400: Fatigue Design, Part 2600: Design Example.

7. Relative to a) loading, b) safety elements, and c) compatible supporting standards observe further any ① NAD - National Application Documents, and ② Application Rules.