Analytical and Experimental Approach to Evaluate the Cumulative Damage of Medium and High Strength Steel Welded Plates

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ABSTRACT. *The use of high grade steels shall permit to design and to manufacture lighter structures made by a large use of welded plates such ships, bridges, off shore structures etc., increasing their safety too. A large experimental activity has been scheduled carrying out fatigue tensile tests on a great number of welded joint full size thickness specimens. Butt and transverse stiffener welded joints, both under constant and variable amplitude loads have been considered. Four steel plates, thickness 10 and 30mm, have been considered in three strength levels: standard grade (S355N, normalized and S355M, with thermo-mechanical treatment), medium grade (S690Q) and a high strength steel (S960Q). In order to investigate the crack path and the subsequent failure of the welded joint a metallographic analysis has been carried out. The assessment of the fatigue behaviour by Miner rules has been unsuccessful. By making changes to Miner damage rule and taking into account of the Double Linear Damage Rule (DLDR) meaningful estimates of the fatigue life have been obtained.*

INTRODUCTION

Great emphasis has been placed in the recent years, particularly in the transportation sector, on the need to reduce the weight of steel structure in order to facilitate fabrication, reduce running costs, to improve fuel efficiency and to increase the safety.

Most of the attention, however, has been focused on relatively lightweight, lightly loaded structures and larger, more heavily loaded structures have been neglected.

Weight reduction may be achieved by using modern, high strength steels which can allow thinner and hence, lighter sections, also through the use of innovative design concept allowed by high grade strength steels.

The aim of this paper is to explore the potential of high grade steel plates in terms of fatigue resistance of different figures of welded joints typically used to manufacture welded components in shipyards, in offshore applications, in railway bridges, etc. assembled in superstructures submitted to repeated heavy loads in service.

Metallographic investigations on welded joints and criteria to obtain the best fatigue design applying cumulative damage criteria have been carried out.

The results discussed in this paper is comes from activities carried out within an European project sponsored by ECSC (European Coal and Steel Community)[1].

EXPERIMENTAL PROCEDURES

Materials

Chemical composition and mechanical characteristics of the considered steels have been reported in Table 1 and Table 2, respectively. Steel grade Fe E 355, largely considered in Eurocode III to manufacture structural welded joints, has been selected in two different standard production conditions: normalized (S355N) and thermo mechanically treated. (S 355 M).

Two innovative steel plates of medium and high strength levels, not yet considered in the above mentioned Eurocode III, have been involved: Fe E 690 (water quenched, S690Q) and Fe E 960 (water quenched, S960Q).

The investigation was carried out with two types of joints, butt-joint and cruciform joints with thickness plates of 10 mm and 30 mm. The orientation of weld position was perpendicular to the rolling direction.

Gas Metal Arc Welding (GMAW) and Submerged Arc Welding (SAW) this latter only for S355M, have been used.

The specimens 100mm WIDE and 500mm LONG were cut from large welded plates (1250 mm). Care has been used to cut the specimens from the plate to avoid any other residual stresses.

Table 1. Chemical composition of steel plates (mass pct).

Materials	Thickness [mm]	C	Si	Mn	P	S	Mo	Ni	Cr	V	Nb	Ti
S 355 N	10	0.170	0.120	1.34	0.013	0.0040	0.007	0.022	0.036	<0.005	<0.005	0.016
	30	0.170	0.400	1.48	0.014	0.0010	0.003	0.030	0.037	<0.005	<0.005	0.010
S 355 M	10	0.082	0.278	1.12	0.010	0.0009	0.010	0.036	0.029	0.000	0.018	0.008
	30	0.075	0.322	1.56	0.012	0.0006	0.006	0.033	0.028	0.001	0.021	0.014
S 690 Q	10	0.156	0.287	1.20	0.013	0.0008	0.110	0.033	0.045	0.050	0.001	<0.005
	30	0.170	0.620	0.93	0.011	0.0030	0.420	0.021	0.880	0.003	<0.005	0.023
S 960 Q	10	0.170	0.380	1.48	0.010	0.0020	0.450	0.024	0.590	0.047	<0.005	0.004
	30	0.168	0.278	0.90	0.017	0.0030	0.510	0.980	0.480	0.040	0.013	<0.005

Table 2. Mechanical properties.

Material	Thickness [mm]	Specimen direction	Yield Strength [MPa]	Tensile strength UTS [MPa]	Elongation A [%]	Notch impact energy CV (-40°C), [J]
S 355 N	10	Longitud.	367	532	35	159
		Transv.	365	531	35	71
	30	Longitud.	374	559	36	192
		Transv.	378	560	36	150
S 355 M(*)	10	Transv.	424	487	34.4	
	30	Transv.	422	524	33.5	356
S 690 Q(*)	10	Transv.	820	852	16.7	131
	30	Longitud.	786	870	22	156
		Transv.	784	868	21	87
S 960 Q(*)	10	Longitud.	1003	1064	19	66
		Transv.	1003	1062	19	57
	30	Longitud.	998	1072	15.5	43

(*) tensile test has been carried out only the in reported rolling directions

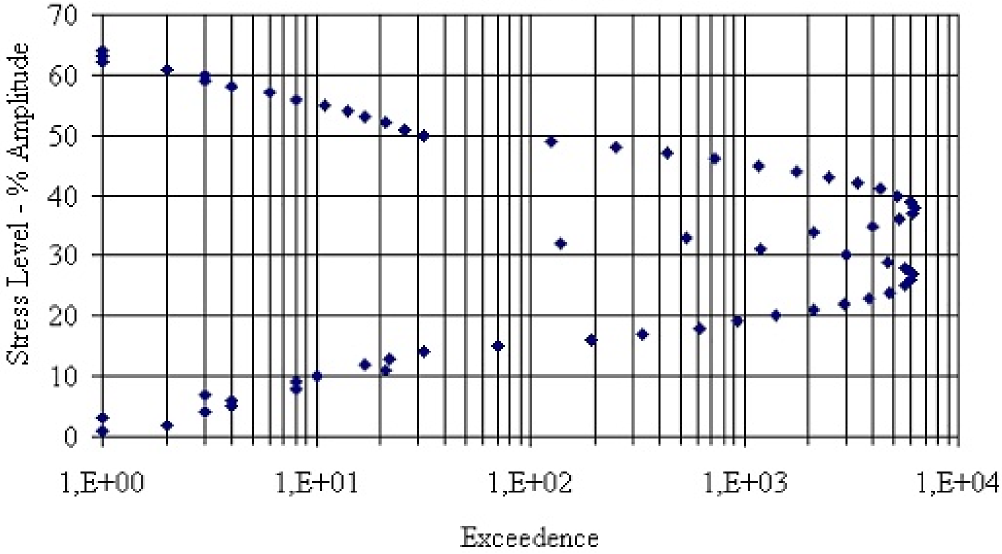
Fatigue Testing

Fatigue tests have been carried out using different layouts. Small thickness specimens (10 mm) have been tested applying tensile fatigue stresses, whilst bending test has been arranged for 30 mm thick specimens. MTS and Schenck servo hydraulic testing machines have been used.

The failure was detected by the variation of 20% of initial compliance of the specimens. This criterion permits to spot the test before the complete failure of the joints. Fatigue strength has been assessed at 2 million cycles (Nf=2·106 cycles). It corresponds to the conventional fatigue limit at constant amplitude and denominated fatigue class FAT in Eurocode III. Same criterion has been used for variable amplitude loads. In order to reproduce service loads, the fatigue tests have been performed with three different spectrum loads: constant amplitude, variable amplitude and variable amplitude with the presence of overloads greater than 40% of the maximum load peak present in the variable spectrum (Fig. 1).

The load applied has Gaussian spectrum with stress ratio R=0 and R=-1, that is an alternating load. This type of stress sequence is derived from real stresses applied to a welded joint during in service life.

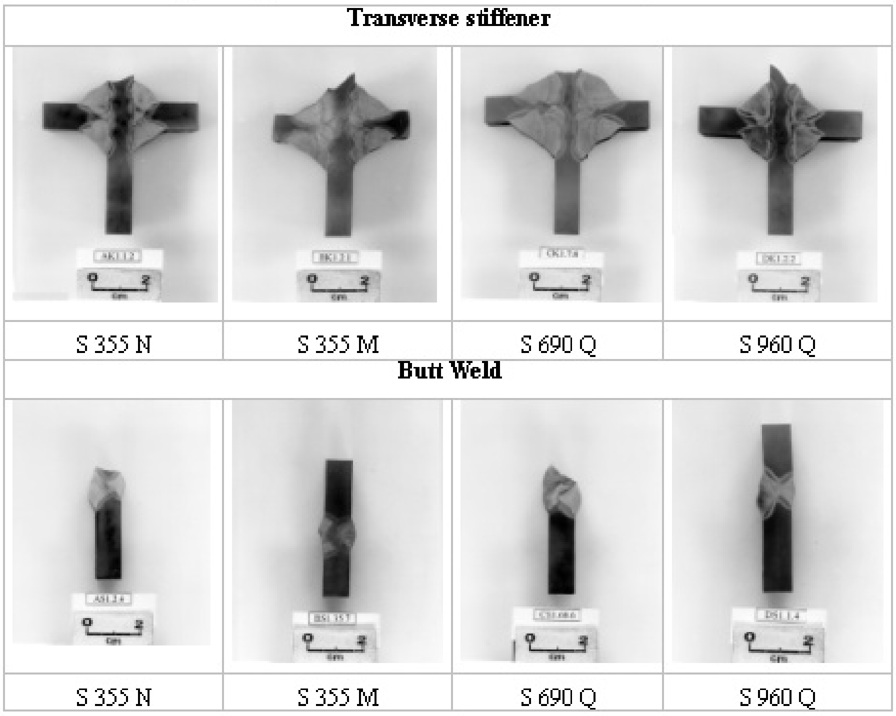
Fig. 1. Exceedence Diagram of Amplitude
R= -1 with Overload



RESULTS AND DISCUSSION

The macrographs of typical failures occurred in many cases have been documented in Fig. 2.

Fig. 2. Typical failures occured in welded joints



As expected all the failures occurred at the weld toe where grain coarse and maximum stress concentration occurs due to undercuts. No failures due to presence of defects in the weld or in parent material have been noticed.

The results obtained from the fatigue tests performed with constant and variable amplitude loads have been used to carry out a post-data analysis to evaluate by models the cumulative damage and establish suitable fatigue design for welded joints.

Miner Damage Rule

The cumulative rule proposed by Miner has the advantage to be very simple and, with some opportune attentions can be applied to welded joints even in this case of variable amplitude load.

In a general stress history the damage sum is computable by:

$$D = \sum_i \frac{n_i}{N_i} \tag{1}$$

where:

n_i number of cycles at constant stress range S_i

N_i number of cycles to fracture for the considered stress range S_i

i number of different stress ranges in the spectrum load.

It is of common knowledge [2] that, with a damage value equal to D=1, the specimen can be considered broken, but a question arises: can Miner be applied even to a random load applied on welded joints?

Apart from the considerations due to the presence of welded joint, fatigue life depends even by the temporal sequence of applied load, hence the damage in a cycle is not only proportional to the stress in the considered cycle, but even by stress interaction effects.

Moreover, it is important to take into account the stress sign, tension or compression, and the ratio $R=\sigma_{min}/\sigma_{max}$. For these reasons Miner rule can lead to unrealistic fatigue life prediction. Table 3. reports the stress amplitude fatigue limit at R=-1 for all specimens, butt welded (BW) and transverse stiffener (TS).

Table 3. Fatigue limit evaluated by Miner rule, for all types of specimens. The spectrum load is Gaussian with overloads.

		FATIGUE LIMIT FOR t=10mm [MPa]			FATIGUE LIMIT FOR t=30mm [MPa]		
Material	Joints	Experimental data	Miner (D=1)	Miner modified	Experimental data	Miner (D=1)	Miner modified
S 355 N	BW	190	304	207 (D=0.1)	213	354	206 (D=0.1)
S 355 M	BW	193	225	181 (D=0.1)	192	275	186 (D=0.25)
S 690 Q	BW	145	179	101 (D=0.1)	221	365	213 (D=0.15)
S 960 Q	BW	190	421	172 (D=0.05)	275	297	273 (D=0.75)
S 355 N	TS	140	180	141 (D=0.5)			
S 355 M	TS	125	167	127 (D=0.5)	171	237	172 (D=0.35)
S 690 Q	TS	130	164	139 (D=0.5)	268	328	265 (D=0.5)
S 960 Q	TS	240	260	219 (D=0.5)	155	237	154 (D=0.25)

Miner rule has been applied and compared with the experimental results; for every situation has been found a damage value, reported as Miner modified, which predicts a fatigue life, less or equal to experimental test, that means Miner rule is NOT CONSERVATIVE and not useful to predict the damage for welded joints.

From obtained data can be deduced that a damage value of 0,1 can be accepted for butt weld joint and 0,5 for transverse stiffener as far as t=10mm, but is not a general rule: unpredictable results can be obtained, for example if t=30mm. In this case there is not a unique value.

The Double Liner Damage Rule and Fracture Mechanics

The study on fracture mechanics identifies two states: crack initiation and crack growth. Miner rule is not the right way because it is linear and does not take in account this two fundamental and separate mechanisms.

Since 1950 were proposed formula that linked fracture mechanic with fatigue damage rules, and in last year many authors proposed a damage rule function of crack depth, a_0, also known as Damage Curve Approach [3]:

$$D = \left[\frac{1}{c}\right]\left[a_0 + (c - a_0)\left(\frac{n}{N}\right)^{\frac{2}{3}N^{0.4}}\right] \tag{2}$$

where:

n number of cycles at the stress range $\Delta\sigma$;

N number of cycles to failure at $\Delta\sigma$

c=0.18 critical crack depth, in inches.

From Eq. (2) it can be noticed that lower is the applied load (hence the fatigue life N is "higher"), higher is the time for crack nucleation. That means the fatigue assessment is related to the fatigue crack initiation at beginning and when the cycles increase the criterion takes into account the growing crack phase, like into fracture mechanical approach. In other words, when the damage is above a certain value, the crack depth/length rises up to material failure. If the applied load low is higher and N low, the crack growth time shall be considered preponderant over crack initiation.

The literature indicates the tangent slope for a low cycle numbers still not match the experimental data and, even if more realistic than Miner rule, it is does not satisfactory.

In order to meet the experimental results, Manson and Halford equation has been considered. They proposed to add a term at DCA formula, with higher influence for a lower number of cycles (Double Damage Curve Approach, DDCA):

$$\mathrm{D} = \left[\frac{\mathrm{n}}{\mathrm{N}}\right]\left\{\mathrm{q}_1^{\gamma} + [1 - \mathrm{q}_1^{\gamma}]\left[\frac{\mathrm{n}}{\mathrm{N}}\right]^{\gamma(\mathrm{q}_2 - 1)}\right\}^{1/\gamma} \tag{3}$$

The use of Eq. (3) is not easily applicable when the number of tension levels is high, but an adequate approximation can be obtained with two segments, one tangent to DCA for a low damage value, and the other segment tangent for D=1

The goal of Manson e Halford [4-6] was to approximate Eq. (3) in two segments that shall be representative of the crack initiation and crack propagation mechanism present in fatigue. Their studies lead to the Double Linear Damage Rule (DLDR), that was subsequently modified by other authors [7]. The only difference between the DLDR and DCA is that the approximation is mathematical and there is not, unfortunately, any link between fracture mechanics and DLDR. For this case, it is proper to individuate them only as phases I and II, before or after the knee-point, and not as initiation and stable crack growth

The comparison between these equations is represented in Fig.3.

Fig. 3. Comparison between DCA, DDCA and DLDR

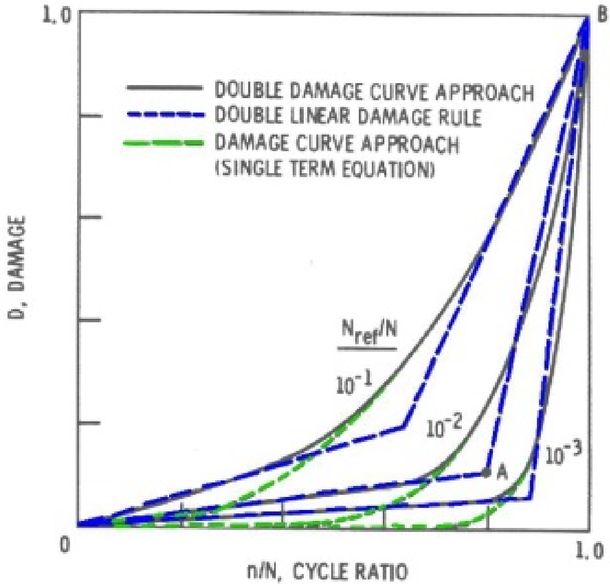
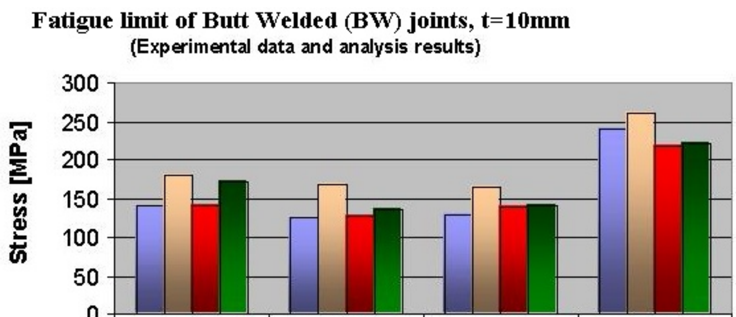


Figure 4 shows the results of the fatigue survival obtained from Miner, Miner Modified, DLDR approach and the effective experimental fatigue results.

Figure 4. Fatigue life limit under a random spectral load with overloads.



	S355N	S355M	S690Q	S960Q
Experimental data	140	125	130	240
Miner (D=1)	180	167	164	260
Miner modified	141	127	139	219
DLDR	172	135	142	222

CONCLUSIONS

Applying DLDR to experimental data leads to interesting results. Considering the fatigue limit at $2x10^6$ cycles under random load with overloads, the tests show that calculation obtained with DLDR match experimental data. Moreover, they are close to the prediction by Miner modified equation, even if the results are only achieved by constant amplitude behaviour and not after having compared experimental data with a suitable damage value as Miner modified needs. The DLDR approach meets our requirements of an analytical method to evaluate the fatigue life of welded joints under random loads and with overloads. More accurate results are obtained considering the constant amplitude data for a 10% life probability of survival.

Regarding material fatigue properties, experimental data highlighted the fatigue limit under random load is not so different for low, medium and high strength steel: this is caused by high residual stress levels and high notch factor for steels S690Q and S960Q. However the advantage of use high grade strength steel plates must be met in presence of unexpected high over-stresses.

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