CRITICAL ANALYSIS OF CURRENT CODES ON FATIGUE DESIGN OF WELDED JOINTS

Giuseppe Chiofalo, Vincenzo Crupi, Eugenio Guglielmino, Letterio Scibilia
DCIIM, Faculty of Engineering, University of Messina, Messina, Italy

SUMMARY

The aim of this paper is focused on the critical analysis of the recommendations, reported in some current codes, for the fatigue strength assessment of welded structures in ship. This paper collects a large amount of experimental data for fatigue assessment of welded joints, which differ for: base material (steel, aluminium alloys), yield stress, welding technique, geometry (i.e. butt, cruciform, T-shaped joints), thickness, fatigue test parameters (frequency, stress ratio). The fatigue design specifications were compared to relevant published experimental data to analyse the code reliability and limitations. Moreover, the available data were analysed to investigate the influence of different parameters (such as material, geometry, thickness, stress ratio) on the difference between the recommended data and the fatigue test results.

Experimental tests were also carried out on T-shaped aluminium alloy welded joints to analyse the influence of stress ratio \( R \).

NOMENCLATURE

- \( f \) frequency (s\(^{-1}\))
- \( f(R) \) negative enhancement factor
- \( m \) negative inverse slope of the \( S-N \) curve in bi-logarithmic scale
- \( n \) number of specimens
- \( s \) standard deviation of data in the \( S-N \) curve
- \( ABS \) American Bureau of Shipping
- \( C-NLC \) cruciform non load carrying
- \( FAT \) fatigue class (N mm\(^{-2}\))
- \( IIW \) International Institute of Welding
- \( N \) number of cycles
- \( N_F \) number of cycles to failure
- \( R \) stress ratio
- \( R_{exp} \) stress ratio of experimental \( S-N \) curves
- \( \delta_{ABS} \) percentage difference between experimental and ABS data
- \( \delta_{EC} \) percentage difference between experimental and Eurocode data
- \( \delta_{IIW} \) percentage difference between experimental and IIW data
- \( \sigma_r \) rupture stress (N mm\(^{-2}\))
- \( \sigma_y \) yield stress (N mm\(^{-2}\))
- \( \Delta\sigma \) stress amplitude (N mm\(^{-2}\))
- \( \Delta\sigma_0 \) endurance limit as expected with the \( S-N \) curve at \( 5 \times 10^6 \) cycles (N mm\(^{-2}\))

1. INTRODUCTION

The fatigue analysis is an important step of ship design and, as is well known, welds are often regions of weakness and their quality directly affects the structural integrity. They are intrinsically weak, due to the presence of crack-like defects along with high stress concentration effects and tensile residual stresses caused by the thermal welding process itself. Thus, clear design guidelines are needed to ensure that fatigue failures are avoided in welded structures. The design of welded structures is commonly carried out by means of rules which impose conservative values of the allowable fatigue stress, or take into account possible defects, residual stresses, corrosion and so on. At the same time, it is useful, especially in the design of critical detail, to have knowledge of the actual strength of welded structures to increase confidence in the design.

The aim of this paper is focused on the critical analysis of the recommendations, reported in some current codes (International Institute of Welding [1], Eurocode [2, 3], American Bureau of Shipping [4] recommendations), to the fatigue strength assessment of welded structures in ship. The recommendations are based on the assumption that the \( S-N \) curves of welded joints with different geometries have about the same slope for a specific material. Thus, for each joint type, it is possible to define the relevant \( FAT \) (fatigue class) as the fatigue strength at a specific life, usually \( 2 \times 10^6 \) cycles.

The \( S-N \) curves are obtained from constant amplitude fatigue tests, using least-squares fitting of experimental fatigue data and the standard equation:

\[
\Delta\sigma^m N = C
\]  

(1)

where \( m \) and \( C \) are fitting constants. The regression lines fitted by eq. (1), taking logN as the dependent variable, represent the \( S-N \) curve at the 50 % probability of survival (mean line).

Considering the randomness of the fatigue test results, the IIW and Eurocode analyse the fatigue data using a statistic method, assuming a Gaussian log-normal distribution, and refer to characteristic values (subscript
k). These are values at a 95 % survival probability in reference to a two-sided 75 % confidence level of the mean. They are established by adopting curves lying approximately two standard deviations (for a great number of specimens) of the dependent variable from the mean.

The characteristic value can be figured out by the following procedures:

1. computing the stress range \( \Delta \sigma \) and fatigue life \( N \),
2. computing the exponential \( m \) and constant \( \log C \) in the formula below:

\[
mlg \Delta \sigma + \log N = \log C
\]  

(2)

in particular it is worth to remark as IIW considers \( m \) constant and equal to 3 for all welds,
3. figuring out the nominal value \( X_m \) and standard deviation \( s \) of \( \log C \) through \( m \),
4. supposing \( X_i \) is the logarithm value of test record, the formulas for counting characteristic values can be obtained as follows:

\[
X_m = \frac{\sum X_i}{n}
\]  

(3)

\[
s = \sqrt{\frac{\sum (X_m - X_i)^2}{n-1}}
\]  

(4)

\[
X_K = X_m - k \cdot s
\]  

(5)

where \( n \) is the number of specimens and the value of \( k \) corresponding to \( n \) is listed in documentation and for a great number of specimens can be considered equal to 2 [1-3].

Moreover the design S-N curves refer to a stress ratio \( R \leq 0.5 \) to take into account the residual stress effects. For stress ratio \( R < 0.5 \), a fatigue enhancement factor \( f(R) \) may be considered by multiplying the fatigue class of classified details by \( f(R) \) [1, 2]:

\[
\begin{align*}
f(R) &= 1.6 & \text{for } R < 1 \\
f(R) &= -0.4R + 1.2 & \text{for } -1 \leq R \leq 0.5 \\
f(R) &= 1 & \text{for } R > 0.5.
\end{align*}
\]  

(6)

In the nominal stress approach, the S-N curves, obtained for each class from fatigue tests, appear in many codes and standards [1-3] and are used in conjunction with the cyclic load history expressed in terms of nominal stress ranges evaluated at the detail site. However, in real structures nominal stresses are not always easy to be determined.

The nominal stress approach, widely industrially used, is also accepted by some of the major ship Classification Societies. The fatigue assessment procedures, used by the Classification Societies, have been applied, within a comparative study, to the fatigue assessment of a pad detail on the coaming of a Panamax container ship [5]. The situation appeared to be unsatisfactory, particularly for the large scatter of results, demonstrating that several procedures, including the direct load calculation, yield only conservative results [5]. Nevertheless, the code recommendations have some shortcomings: they do not consider the well known thickness effect and the selection of the class can be very subjective, since the classification is based not only on the joint geometry but also on the dominant loading mode.

In order to overcome these difficulties, innovative methods has been applied by the authors to predict the fatigue behaviour of welds used in ship structures [6-9].

The present paper collects a large amount of fatigue data, published during the past 10–15 years, referred to welded joints, which differ for: base material (steel, aluminium alloys), yield stress, welding technique, geometry (i.e. butt, cruciform, T-shaped joints), thickness, fatigue test parameters (frequency, stress ratio). The experimental fatigue data, available from literature and by our own experimental tests, are compared to the design fatigue curves, reported in some current codes and standards, to analyse the code reliability and limitations. The available data were analysed to investigate the influence of different parameters (such as material, geometry, thickness, stress ratio) on the difference between the recommended data and the fatigue test results.

Moreover, experimental tests were carried out on T-shaped welded joints, made of aluminium alloy, to analyse the influence of stress ratio \( R \).

The research activity developed consists on three phases:

1. comparison between different codes,
2. comparison between design curves and literature data,
3. experimental tests carried out at different stress ratio \( R \) values.

2. COMPARISON BETWEEN DESIGN CODES

2.1 THE WELDED JOINTS ANALYSED

A comparison was made between some of the most common design codes for the assessment of fatigue life of welded joint. The codes considered were: Eurocode [2, 3] and IIW [1] for steel and aluminium joints, ABS [4] for steel.

As mentioned above, codes define several design curves, so that every welded detail is linked to a specific curve. All the details are classified by mean of their geometry, type, load direction, way of failure.

In every code no distinction is drawn between different welding process, but only there is the need to utilise mechanised welding to achieve continuous welds without stop/starts, even if the design curve are based by data obtained from arc weld.
For an easier assessment between different codes, welded details have been assembled in seven categories: 1) transverse butt welds without backing strip; 2) transverse butt welds with backing strip; 3) longitudinal gusset; 4) transverse non-load-carrying cruciform or tee joints; 5) load carrying cruciform or tee joints; 6) tubular and rectangular hollow section welds with connection to plate; 7) nodal hollow section welds. For each category, welds made of steel and aluminium alloy were analysed.

2.2 RESULTS AND DISCUSSION

2.2.1 Transverse butt welds without backing strip
For this detail, three different weld types has been considered: both side ground flush 100% controlled with NDT, both side with a toe angle smooth transition, one side joint (n. 1, 2, 3, 6, 7 in Table 1). As shown in Table 1, every code provides a similar FAT for each class, but Eurocode gives values of $m$ higher than 3 for aluminium alloy welds, producing a different fatigue life prediction at low cycles. For not ground flush details (n. 2, 3 in Table 1), the IIW provides different FAT values as a function of toe angle.

<table>
<thead>
<tr>
<th>n.</th>
<th>Description</th>
<th>Examples</th>
<th>STEEL (IIW)</th>
<th>STEEL (EUROCODE)</th>
<th>ALUMINIUM ALLOY (IIW)</th>
<th>ALUMINIUM ALLOY (EUROCODE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Complete penetration transverse butt joints welded from both sides with weld cap ground flush to plate, free from significant defects</td>
<td><img src="image1.png" alt="Image" /></td>
<td>125-3</td>
<td>112-3</td>
<td>C –124-3.5</td>
<td>50-3</td>
</tr>
<tr>
<td>2</td>
<td>Complete penetration transverse butt joints welded from both sides, made manually or by an automatic process other than submerged arc, all runs made in downhand position, smooth transition</td>
<td><img src="image2.png" alt="Image" /></td>
<td>100-3</td>
<td>90-3</td>
<td>D 91–3</td>
<td>40-3</td>
</tr>
<tr>
<td>3</td>
<td>Welds not satisfying conditions for joint type (b)</td>
<td><img src="image3.png" alt="Image" /></td>
<td>80-3</td>
<td>80-3</td>
<td>E 80-3</td>
<td>32-3</td>
</tr>
<tr>
<td>4</td>
<td>Complete penetration transverse butt joints welded from one side on a permanent ceramic backing welded to the plate</td>
<td><img src="image4.png" alt="Image" /></td>
<td>80-3</td>
<td>112-3</td>
<td>F 68-3</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Complete penetration transverse butt joints welded from one side on a permanent ceramic backing without fillet welds</td>
<td><img src="image5.png" alt="Image" /></td>
<td>71-3</td>
<td>100-3</td>
<td>F 68-3</td>
<td>25-3</td>
</tr>
<tr>
<td>6</td>
<td>Complete penetration transverse butt joints welded from one side without permanent ceramic backing, root controlled by NDT</td>
<td><img src="image6.png" alt="Image" /></td>
<td>71-3</td>
<td>-</td>
<td>-</td>
<td>28-3</td>
</tr>
<tr>
<td>7</td>
<td>not NDT</td>
<td><img src="image7.png" alt="Image" /></td>
<td>45-3</td>
<td>36-3</td>
<td>-</td>
<td>18-3</td>
</tr>
</tbody>
</table>

Table 1: Butt welds, transverse loaded

For an easier assessment between different codes, welded details have been assembled in seven categories: 1) transverse butt welds without backing strip; 2) transverse butt welds with backing strip; 3) longitudinal gusset; 4) transverse non-load-carrying cruciform or tee joints; 5) load carrying cruciform or tee joints; 6) tubular and rectangular hollow section welds with connection to plate; 7) nodal hollow section welds. For each category, welds made of steel and aluminium alloy were analysed.

2.2 RESULTS AND DISCUSSION

2.2.1 Transverse butt welds without backing strip
For this detail, three different weld types has been considered: both side ground flush 100% controlled with NDT, both side with a toe angle smooth transition, one side joint (n. 1, 2, 3, 6, 7 in Table 1). As shown in Table 1, every code provides a similar FAT for each class, but Eurocode gives values of $m$ higher than 3 for aluminium alloy welds, producing a different fatigue life prediction at low cycles. For not ground flush details (n. 2, 3 in Table 1), the IIW provides different FAT values as a function of toe angle.

2.2.2 Transverse butt welds with backing strip.
The codes give about the same value of slope $m$ for this category (n. 4, 5 of Table 1). Eurocode provides FAT values generally higher than the others.

2.2.3 Longitudinal gusset.
For steel longitudinal gusset welded on beam flange (bulb or plate), every code gives as different FAT values as long is the gusset (n. 1 - 4 of Table 2), but in different way. For example, ABS specifies only if the length of gusset is more or less than 150 mm.
<table>
<thead>
<tr>
<th>n.</th>
<th>Description</th>
<th>Examples</th>
<th>STEEL ALUMINIUM ALLOY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>IIW EUROCODE ABS IIW EUROCODE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FAT-m</td>
<td>FAT-m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FAT-m</td>
<td>FAT-m</td>
</tr>
</tbody>
</table>

**Welded longitudinal attachment**

1. $1 \leq 50$ mm
   - $80-3$ $80-3$ F 68-3 $28-3$

2. $50 < l \leq 150$ mm
   - $71-3$ $71-3$ F 68-3 $25-3$
   - $(50 < l \leq 100)$

3. $150 < l \leq 300$ mm
   - $63-3$ $50-3$ F 60-3 $20-3$

4. $l > 300$ mm
   - $50-3$ $50-3$ F 60-3 $18-3$

The Class depends by the dimensions of the weld.

---

Transverse non load carrying attachments, not ticker than main plate (i.e. C-NLC)

5. K-butt weld, toe ground
   - $100-3$ F 68-3 $36-3$

6. Two-sided fillets, toe ground
   - $100-3$ F 683 $36-3$

7. Fillet weld(s), as welded
   - $80-3$ $80-3$ F 68-3 $28-3$ $28-3.2$

8. Thicker than main plate
   - $71-3$ F 68-3 $25-3$ $25-3.2$

Table 2: Welded attachments on the surface of a stressed members

<table>
<thead>
<tr>
<th>n.</th>
<th>Description</th>
<th>Examples</th>
<th>STEEL ALUMINIUM ALLOY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>IIW EUROCODE ABS IIW EUROCODE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FAT-m</td>
<td>FAT-m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FAT-m</td>
<td>FAT-m</td>
</tr>
</tbody>
</table>

**Load carrying cruciform (or T, K-butt) welds**

1. Full penetration, weld toe ground
   - $80-3$ $71-3$ F 68-3 $28-3$ $28-3.2$

2. Full penetration
   - $71-3$ $71-3$ F 68-3 $25-3$ $28-3.2$

3. Partial penetration, toe failure
   - $63-3$ $36-3$ F 260-3 $22-3$ $28-3.2$

4. Partial penetration, root failure
   - $45-3$ $36-3$ F 260-3 $16-3$ $18-3.2$

**Lap joints**

5. Fatigue of parent metal
   - $63-3$ $63-3$ F 260-3 $22-3$ $22-3$
   - $(ed \geq 10 \text{ mm})$

6. Fatigue of weld throat
   - $45-3$ $45-3$ G 50-3 $16-3$ $14-3.2$
   - $(ed < 10 \text{ mm})$
   - ed = edge distance

Table 3: Welded joints with load carrying welds
2.2.4 Transverse non load carrying joints
For aluminium welds with transverse non load carrying attachments (n. 5 - 8 of Table 2), the design curves are rather coincident. For steel welds, Eurocode and IIW design curves are very similar, but ABS provides lower FAT values.

2.2.5 Load carrying cruciform or tee joints
As can be seen in Table 3, codes make a distinction between full and partial penetration welds. Moreover IIW distinguishes the full and partial penetration welds in other two classes. However, it’s worth to remark the considerable lower FAT provided by Eurocode for partial penetration welds. The reason of this remarkable gap is that Eurocode defines very careful when a partial penetration weld has the same fatigue strength as a full penetration one [2]. So it could be reasonable to consider, in the appropriate welding condition, a fillet penetration weld has the same fatigue strength as a full penetration weld, and, as consequence, according to the procedure explained in Eurocode [2], its FAT has to be increased to the next higher fatigue class and also its slope $m$ changes.

2.2.6 Tubular and rectangular hollow section welds with connection plate
As for aluminium welds, only IIW provides the design curves. From the data reported in the rules, it results that the tubular section allows always to achieve a higher fatigue strength than rectangular hollow section.

2.2.7 Nodal hollow section welds
It’s worth to remark that different codes don’t give the same definition of these weld details. Eurocode 3 makes a distinction between tubular and rectangular sections and also considers oblique joints [2]. ABS doesn’t provide any information about the direction of the welded hollow section beams and considers only the tubular sections. IIW classifies in the same class rectangular and tubular sections, and considers only perpendicular welded beams.

Even if aluminium welded hollow section joints are finding increased use, the design codes are not available yet. The reason is probably due to the presence of so numerous geometry and loading conditions, that makes difficult to define unifying classes. The hot spot stress approach seems to be suitable for the design of these details. This approach has been used extensively in the offshore industry for the fatigue assessment of steel tubular joints. Mcdonald [10] evaluated a design $S$-$N$ curve, based on hot spot stress, for rectangular hollow section Tee joints, subjected to four points bending, and the Stress Concentration Factor was determined from strain gauge measurements according to the IIW procedure.

The codes considered give a more or less detailed description of welds details. As far as fatigue life prediction concerned, Eurocode and IIW curves appear very similar, but sometimes IIW gives higher values than those reported by Eurocode. In the other hand, ABS provides fatigue strength of steel welds generally lower than others.

3. COMPARISON BETWEEN DESIGN CODES AND LITERATURE DATA

3.1 THE WELDED JOINTS ANALYSED
All the design $S$-$N$ curves for welded joints are claimed to have been derived from experimental data by linear regression analysis so that they represent approximately 97.7% probability of survival. However, it is not always clear how this has been achieved. It is evident that in most cases some judgement has been applied and some assumptions, like the slope of the design $S$-$N$ curve, have been imposed. It is also claimed that special attention was paid to the provision of data relevant to real structures, particularly with respect to the influence of tensile residual stresses and so the fatigue design specifications refer to a stress ratio $R=0.5$.

In order to provide a basis for judging the validity of the proposed design curves, relevant published data have been assembled and compared with some of the design curves. Reference was made to recent papers [11-21] reporting the experimental $S$-$N$ curves and the standard deviation $s$. The experimental $S$-$N$ curves, obtained through a linear regression of the experimental data, correspond generally to a survival probability of 50% and to a stress ratio $R$ different than 0.5. In order to compare their fatigue resistance data ($m$, FAT, $\Delta\sigma_0$) with those reported in the codes, the experimental $S$-$N$ curves have to be analysed statistically to establish mean curve and statistical lower bound, usually mean minus 2 standard deviations $s$. The design $S$-$N$ curve were, also, changed to take into account the influence of the stress ratio. According to the codes [1, 3], for $R<0.5$ the new value of FAT is obtained by:

$$FAT(R) = FAT(0.5) \cdot f(R)$$  \hspace{4cm} (7)

The stress range $\Delta\sigma$, corresponding at $10^4$ cycles, doesn’t change, so the design $S$-$N$ curve corresponding to a value of $R$ different than 0.5, is drawn interpolating the new value of FAT with the stress range at $10^4$ cycles.

Tables 4 and 5 report the geometries, materials, yield stresses, thicknesses and stress ratio $R$ values of the welded joints investigated respectively for aluminium alloy and steel. Moreover, for each welded joint, the following values are shown in the Tables:

- FAT, $m$ of experimental $S$-$N$ curves at $P_s=50\%$ and $R_{exp}$,
- percentage difference $\delta\%$ of design fatigue resistance data (FAT, $m$, $\Delta\sigma_0$) at $R_{exp}$ with respect to the characteristic data ($P_s=97.7\%$) obtained by the experimental $S$-$N$ curves.

The percentage difference $\delta\%$ of FAT is defined as:

$$\delta\% = 100 \frac{FAT_{97.7\%exp} - FAT_{97.7\%code}}{FAT_{97.7\%code}}$$ \hspace{4cm} (8)
where FAT$_{97\%exp}$ and FAT$_{97\%code}$ are respectively the characteristic values of FAT obtained by literature and codes. The same equation is used to assess the percentage difference $\delta \%$ of $m$ and $\Delta \sigma_0$. Compared with the experimental data reported in literature [11-21], design curves of analysed codes (Eurocode [2, 3], IIW [1] and ABS [4]) appear particularly conservative. Analysing the data of Tables 1–5, it results that the mean values of FAT (Ps= 50 \%), obtained by experimental tests [11-21], are higher than those reported in the codes. This result can be explained by the fact that the codes not mention weld quality and consider values of admissible stress on the safe side, since they take into account the all acceptable qualities and therefore consider a quality level rather low to be safe [19].

Weld quality have a great influence on the fatigue strength of welded joints, acting on the conditions of crack initiation at the weld toe. Fatigue strength is known to be closely related to the precise geometrical discontinuity of the welded joint (weld toe radius, flank angle and weld size). The difference of fatigue strength relative to some series of Table 5 (ST-18\% ST-30) and published in literature [19] is consequence of the different qualities of the welds. Depending on the weld qualities, an increase of the endurance limit of some 50 \% has been evaluated [19].

Welding imperfections that may be introduced during fabrication are only partially considered in the conventional fatigue design rules for welded joints. The fatigue rules do not take into account the weld quality; the design $S$–$N$ curves are generally based on laboratory tests of “normal” quality welds, even though the precise definition of normal quality is not always clearly defined. Weld bead geometry depends on welding conditions (welding process, filler metal, welding position) and cannot be precisely defined mainly because parameters such as bead shape and toe radius vary from joint to joint even in well-controlled manufacturing operations. However the percentage differences $\delta \%$, shown in the Tables 4 and 5, are evaluated comparing the characteristic values (Ps= 97.7 \%) of experimental and design data in accordance with eq. (8). Moreover the design $S$–$N$ curves were changed to take into account the $R$ effect of the experimental tests. For some investigated welds, $\delta \%$ has negative value and it means that the design rules could be less conservative than literature data.

The experimental data, reported in literature, are sometimes obtained assembling the results of different series of welded joints, which have the same weld geometry and loading conditions, but differ for base material, yield stress, welding technique, thickness, weld bead geometry. It is confirmed by some investigated series (i.e. AL-1, ST-1, ST-2, ST-31) shown in Tables 4 and 5. Due to large variations in the geometrical parameters of the welded joints, the scatter of the experimental data is generally very pronounced in terms of nominal stress range. For this reason, there is a high decrease of the experimental fatigue strength at Ps= 97.7 \%, achieving negative values of $\delta \%$. It is demonstrated by the high values of standard deviation $s$ for some investigated details with $\delta \% < 0$.

Another explanation of the negative values of $\delta \%$ could be due to the high change of the design $S$–$N$ curve for taking into account the influence of the stress ratio $R$. The fatigue enhancement factor $f(R)$ is too high as it was demonstrated by the experimental results described below.

The data of Table 4 demonstrate that the specifications don’t give good predictions of fatigue behaviour of aluminium alloy welds, because the slope $m$ of the design curve has been imposed equal to about 3. This assumption of the codes could be justified for steel welds (Table 5), but not for aluminium joints that have values of $m$ in the range 4–7 (Table 4).

With regard to the base material of welds, the fatigue design rules and recommendations are available for structural steels, but the increase of stainless steel applications require knowledge about the fatigue behaviour of stainless steel welded structures. Actually it is possible obtaining stainless steels with mechanical properties close to those of structural steels and the higher cost can be reduced by the avoidance of painting or corrosion protection cost. The fatigue strengths of the joint geometries analysed by Niemi et al. [15] are similar to those of identical joints in structural steels. Niemi [15] demonstrated that there is no high variation in fatigue strength resulting from the different yield stresses in the investigated austenitic, austenitic-ferritic, ferritic stainless steels (series ST-7\% ST-12 of Table 5). The fatigue strength of austenitic steel butt joints is different than the other investigated joints and is even lower than the design strength, but this is due, probably, to the limited number of austenitic specimens investigated [15].

The thickness of a welded joint is, also, an important parameter. Fatigue strength is well known to decrease with increasing plate thickness [22], because small welded joints do not contain significant residual stresses. Analysing the results, reported in the Tables 4 and 5, it is clear that the percentage difference between literature and design data depends by the thickness. This trend is more evident in the series ST-13\% ST-16. The experimental fatigue data, expressed in terms of FAT in Table 5, indicate that fatigue strength is relative insensitive to thickness effects for $t<11$ mm (ST-13, S-14) and is subject to an abrupt decrease for higher thicknesses (ST-15, S-16). Moreover the design data refer to traditional welding techniques and there aren’t corresponding design data for not traditional welding process.

Significant improvements of fatigue strength of aluminium alloy welds can be achieved resorting to the somehow new joining technique called Friction Stir Welding (FSW). The process is used commercially in different fields, and for ship structures it concerns mainly decks and bulkheads.
### Table 4: Comparison between experimental and design fatigue data for aluminum welds

<table>
<thead>
<tr>
<th>Series</th>
<th>Joint type</th>
<th>Material</th>
<th>$\sigma_y$ [MPa]</th>
<th>$t$ [mm]</th>
<th>$R$</th>
<th>Experimental $\delta_{EC}$ %</th>
<th>$\delta_{RW}$ %</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL-1</td>
<td>Ground Butt</td>
<td>AA5052, AA5083, AA5086, AA7039</td>
<td>210-400</td>
<td>4-9.5</td>
<td>0</td>
<td>113</td>
<td>5.5</td>
<td>170</td>
</tr>
<tr>
<td>AL-2</td>
<td>Longitudinal (L=40 mm)</td>
<td>AA5083</td>
<td>250-355</td>
<td>8</td>
<td>0</td>
<td>35</td>
<td>4.48</td>
<td>-8</td>
</tr>
<tr>
<td>AL-3</td>
<td>Lap joints</td>
<td>AA5083</td>
<td>250-355</td>
<td>6</td>
<td>0</td>
<td>21.7</td>
<td>3.4</td>
<td>1</td>
</tr>
<tr>
<td>AL-4</td>
<td>Lap joints</td>
<td>AA5083</td>
<td>250-355</td>
<td>8</td>
<td>0</td>
<td>19.8</td>
<td>4.81</td>
<td>-4</td>
</tr>
<tr>
<td>AL-5</td>
<td>Ground Butt</td>
<td>AW5083, AW6082</td>
<td>175-287</td>
<td>5</td>
<td>-1</td>
<td>98</td>
<td>-4.5</td>
<td>-5</td>
</tr>
<tr>
<td>AL-6</td>
<td>Ground Butt</td>
<td>AW5083, AW6082</td>
<td>175-287</td>
<td>5</td>
<td>0</td>
<td>72</td>
<td>6</td>
<td>-7</td>
</tr>
<tr>
<td>AL-7</td>
<td>Ground Butt</td>
<td>AA5083</td>
<td>195</td>
<td>0</td>
<td>0</td>
<td>35</td>
<td>4.18</td>
<td>-2</td>
</tr>
<tr>
<td>AL-8</td>
<td>Ground Butt</td>
<td>AA5083</td>
<td>195</td>
<td>1</td>
<td>-1</td>
<td>56.5</td>
<td>3.4</td>
<td>1</td>
</tr>
<tr>
<td>AL-9</td>
<td>Ground Butt</td>
<td>AW5083, AW6082</td>
<td>195</td>
<td>1</td>
<td>0</td>
<td>35</td>
<td>4.5</td>
<td>-5</td>
</tr>
<tr>
<td>AL-10</td>
<td>Ground Butt</td>
<td>AA5083</td>
<td>195</td>
<td>2</td>
<td>0</td>
<td>35</td>
<td>4.5</td>
<td>-5</td>
</tr>
<tr>
<td>AL-11</td>
<td>Ground Butt</td>
<td>AA5083</td>
<td>195</td>
<td>2</td>
<td>0</td>
<td>35</td>
<td>4.18</td>
<td>-2</td>
</tr>
</tbody>
</table>

### Table 5: Comparison between experimental and design fatigue data for steel welds

<table>
<thead>
<tr>
<th>Series</th>
<th>Joint type</th>
<th>Material</th>
<th>$\sigma_y$ [MPa]</th>
<th>$t$ [mm]</th>
<th>$R$</th>
<th>Experimental $\delta_{EC}$ %</th>
<th>$\delta_{RW}$ %</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-1</td>
<td>Ground Butt Fe 510 D1</td>
<td>405-455</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>131</td>
<td>3.32</td>
<td>-36</td>
</tr>
<tr>
<td>ST-2</td>
<td>C-NLC BS 4360:50D</td>
<td>545-509</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>91</td>
<td>3.21</td>
<td>-4</td>
</tr>
<tr>
<td>ST-3</td>
<td>Ground Butt</td>
<td>545-509</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>136</td>
<td>3.32</td>
<td>-4</td>
</tr>
<tr>
<td>ST-4</td>
<td>C-NLC</td>
<td>545-509</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>124</td>
<td>3.32</td>
<td>-4</td>
</tr>
<tr>
<td>ST-5</td>
<td>T-joint</td>
<td>545-509</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>140</td>
<td>3.32</td>
<td>-4</td>
</tr>
<tr>
<td>ST-6</td>
<td>Longitudinal nlc</td>
<td>545-509</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>85</td>
<td>3.32</td>
<td>-4</td>
</tr>
<tr>
<td>ST-7</td>
<td>Ground Butt</td>
<td>stainless steel, austenitic</td>
<td>453</td>
<td>10</td>
<td>0</td>
<td>151</td>
<td>3.17</td>
<td>-3</td>
</tr>
<tr>
<td>ST-8</td>
<td>Ground Butt</td>
<td>stainless steel, austenitic</td>
<td>453</td>
<td>10</td>
<td>0</td>
<td>181</td>
<td>4.07</td>
<td>-4</td>
</tr>
<tr>
<td>ST-9</td>
<td>Ground Butt</td>
<td>stainless steel, ferritic</td>
<td>274</td>
<td>10</td>
<td>0</td>
<td>143</td>
<td>3.4</td>
<td>-4</td>
</tr>
<tr>
<td>ST-10</td>
<td>Longitudinal nlc</td>
<td>stainless steel, ferritic</td>
<td>274</td>
<td>10</td>
<td>0</td>
<td>92</td>
<td>3.56</td>
<td>-4</td>
</tr>
<tr>
<td>ST-11</td>
<td>Longitudinal nlc</td>
<td>stainless steel, ferritic</td>
<td>453</td>
<td>10</td>
<td>0</td>
<td>91</td>
<td>3.21</td>
<td>-3</td>
</tr>
<tr>
<td>ST-12</td>
<td>Longitudinal nlc</td>
<td>stainless steel, ferritic</td>
<td>274</td>
<td>10</td>
<td>0</td>
<td>131</td>
<td>4.07</td>
<td>-3</td>
</tr>
<tr>
<td>ST-13</td>
<td>C-NLC</td>
<td>HSLA-80</td>
<td>552</td>
<td>6</td>
<td>-1</td>
<td>83</td>
<td>4.09</td>
<td>-5</td>
</tr>
<tr>
<td>ST-14</td>
<td>C-NLC</td>
<td>HSLA-80</td>
<td>552</td>
<td>11</td>
<td>-1</td>
<td>81</td>
<td>3.86</td>
<td>-5</td>
</tr>
<tr>
<td>ST-15</td>
<td>C-NLC</td>
<td>HSLA-80</td>
<td>552</td>
<td>19</td>
<td>-1</td>
<td>52</td>
<td>3.13</td>
<td>-7</td>
</tr>
<tr>
<td>ST-16</td>
<td>C-NLC</td>
<td>HSLA-80</td>
<td>552</td>
<td>25</td>
<td>-1</td>
<td>40</td>
<td>2.73</td>
<td>-7</td>
</tr>
<tr>
<td>ST-17</td>
<td>C-NLC</td>
<td>HSLA-80</td>
<td>552</td>
<td>11</td>
<td>-1</td>
<td>71</td>
<td>3.21</td>
<td>-2</td>
</tr>
<tr>
<td>ST-18</td>
<td>T-joint</td>
<td>E460</td>
<td>550</td>
<td>10</td>
<td>0</td>
<td>149</td>
<td>3.63</td>
<td>10</td>
</tr>
<tr>
<td>ST-19</td>
<td>T-joint</td>
<td>E460</td>
<td>550</td>
<td>10</td>
<td>0</td>
<td>149</td>
<td>3.63</td>
<td>10</td>
</tr>
<tr>
<td>ST-20</td>
<td>T-joint</td>
<td>E460</td>
<td>550</td>
<td>10</td>
<td>0</td>
<td>205</td>
<td>3.25</td>
<td>10</td>
</tr>
<tr>
<td>ST-21</td>
<td>T-joint</td>
<td>E460</td>
<td>550</td>
<td>10</td>
<td>0</td>
<td>165</td>
<td>3.35</td>
<td>10</td>
</tr>
<tr>
<td>ST-22</td>
<td>T-joint</td>
<td>E460</td>
<td>550</td>
<td>10</td>
<td>0</td>
<td>195</td>
<td>4.1</td>
<td>10</td>
</tr>
<tr>
<td>ST-23</td>
<td>T-joint</td>
<td>E460</td>
<td>550</td>
<td>10</td>
<td>0</td>
<td>132</td>
<td>3.2</td>
<td>10</td>
</tr>
<tr>
<td>ST-24</td>
<td>T-joint</td>
<td>E460</td>
<td>550</td>
<td>10</td>
<td>0</td>
<td>150</td>
<td>2.2</td>
<td>10</td>
</tr>
<tr>
<td>ST-25</td>
<td>T-joint</td>
<td>E460</td>
<td>550</td>
<td>10</td>
<td>0</td>
<td>207</td>
<td>4.6</td>
<td>10</td>
</tr>
<tr>
<td>ST-26</td>
<td>T-joint</td>
<td>E460</td>
<td>550</td>
<td>10</td>
<td>0</td>
<td>174</td>
<td>3.2</td>
<td>10</td>
</tr>
<tr>
<td>ST-27</td>
<td>T-joint</td>
<td>E460</td>
<td>550</td>
<td>10</td>
<td>0</td>
<td>165</td>
<td>3.2</td>
<td>10</td>
</tr>
<tr>
<td>ST-28</td>
<td>T-joint</td>
<td>E460</td>
<td>550</td>
<td>10</td>
<td>0</td>
<td>144</td>
<td>3.3</td>
<td>10</td>
</tr>
<tr>
<td>ST-29</td>
<td>T-joint</td>
<td>E460</td>
<td>550</td>
<td>10</td>
<td>0</td>
<td>158</td>
<td>2.8</td>
<td>10</td>
</tr>
<tr>
<td>ST-30</td>
<td>T-joint</td>
<td>E460</td>
<td>550</td>
<td>10</td>
<td>0</td>
<td>195</td>
<td>4.5</td>
<td>10</td>
</tr>
<tr>
<td>ST-31</td>
<td>C-NLC</td>
<td>different steels</td>
<td>9-50</td>
<td>0</td>
<td>0</td>
<td>96</td>
<td>3.29</td>
<td>10</td>
</tr>
<tr>
<td>ST-32</td>
<td>C-NLC</td>
<td>Domex550MC</td>
<td>550</td>
<td>12</td>
<td>0</td>
<td>105</td>
<td>3.1</td>
<td>10</td>
</tr>
</tbody>
</table>

Session B
FSW produces joints of high quality with higher mechanical properties achieving values close to those obtained from the unwelded material and with lower scatter of the experimental data respect to the traditional processes (MIG) [8, 22]. The fatigue properties of friction stir welds in AA5083 were compared to those of corresponding MIG welds by Zhou et al. [17], obtaining a fatigue life of FSW joints 9-12 times longer than that of MIG welds. The comparison with IIW recommendations indicated an excessive conservatism when the design curves are applied to friction stir welds [17].

4. EXPERIMENTAL TESTS

Experimental tests were carried out at different values of stress ratio $R$ to assess the enhancement factor $f(R)$ and to compare the results with code recommendations.

4.1 DESCRIPTION OF TESTS

The T-shaped welded joints analysed are used in ship structures and are made of AlMg 4.5 Mn aluminium alloy (AA5083). Alloy AA5083 is suitable for marine applications thanks its interesting properties, such as low price, good strength and corrosion fatigue.

Figure 1 shows the geometries of joints, which have a width of 50 mm and a thickness of 7 mm.

Tests were performed using an MTS 810 System servo-hydraulic load machine with a 250 kN capacity (Fig. 2).

The preliminary tensile static tests were carried out at a 2 mm/minute rate on two T-shaped welded joints. The results are reported in Table 6.

<table>
<thead>
<tr>
<th>Test</th>
<th>$E$ (MPa)</th>
<th>$\sigma_t$ (MPa)</th>
<th>$\sigma_y$ (MPa)</th>
<th>$\epsilon$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>20278</td>
<td>344</td>
<td>320</td>
<td>18</td>
</tr>
<tr>
<td>Test 2</td>
<td>21374</td>
<td>334</td>
<td>288</td>
<td>17.5</td>
</tr>
</tbody>
</table>
Failure took place in the weld zone of the failed specimens with the crack initiating in proximity of the weld toe, where there are high stress concentrations: all the fracture zones have the typical morphology of the fatigue fracture.

The experimental data were interpolated in the log-log plot by means of a linear regression and consequently the slope $m$ and the endurance limit $\Delta \sigma_0$ were estimated (Table 7). The $S$-$N$ curves are reported in bi-logarithmic scale in Figure 4.

It has to be noted from Table 7 and Figure 4 that there is not a strong difference between the $S$-$N$ curves at $R=0.1$ and $R=0.5$. From the analysis of the experimental results (Table 7) it is clear that the fatigue enhancement factor $f(R)$ is not a linear function of the stress ratio $R$, as defined by the eq. (6) reported in some codes [1, 2], and there is not so much difference between the value of $f(R)$ at $R=0.5$ and at $R=0.1$. Therefore the design fatigue enhancement factor $f(R)$ for $R=0.1$ is not justified by the experimental tests.

The fatigue class corresponding to this aluminium joint type (n. 7 of Table 2) is FAT 28 for IIW and FAT 28 with $m=3.2$ for Eurocode 9. Even in this case the recommendations are very conservative.

5. CONCLUSIONS

The main conclusions of this study can be summarized as follows.

- Eurocode and IIW give similar fatigue life predictions, even if sometimes IIW gives higher values. ABS provides fatigue strength values generally lower than other codes.
- Even if some recommendations offer a more detailed description of the weld joints than others, it’s not always possible to make a definitely classification of an effective joints with his most appropriate design curve, so that the same structural joint can be classified in different categories by different codes.
- As the engineering practice of using various joint geometries and new welding techniques (i.e. FSW) are finding increased use, it’s possible that some welded details are not considered by any codes, such as the hollow section aluminium joints or the friction stir welds.
- The results obtained demonstrate that recommendations are very conservative. This conservatism will became more accentuate with the expected progress in welded structures thanks to the
introduction of new welding techniques and the robotization of the welding process.

- The actual strength of welded structures is influenced by different parameters (weld quality, material, thickness, stress ratio, welding technique), that are not well considered by the rules.
- The tests carried out at different stress ratio $R$ demonstrated that there is not a strong difference between the $S$-$N$ curves at $R$=0.1 and $R$=0.5.

6. ACKNOWLEDGMENTS
The authors are grateful to the Italian naval factory Cantieri Navali Rodriguez for the provision of specimens.

7. REFERENCES


