STRUCTURAL DETAILS IN LIGHTWEIGHT ALUMINIUM CRAFTS: WAYS OF IMPROVING STRUCTURAL RELIABILITY BY APPLYING “SAFE LIFE” VS. “FAIL SAFE” PRINCIPLES

CARLOS MATIAS*, PAULO P. SILVA**, RUI F. MARTINS *

*Universidade Nova de Lisboa, Departamento de Engenharia Mecânica e Industrial,
Faculdade de Ciências e Tecnologia (FCT/UNL)
Campus de Caparica, 2829-516 Caparica, Portugal
rfspm@fct.unl.pt

**Marinha Portuguesa, Direcção de Navios
Departamento de Estudos
Base Naval de Lisboa, 2800-001 Alfeite
pires.silva@marinha.pt

ABSTRACT: This paper presents the results of investigations into static and dynamic properties of structural details of lightweight aluminium crafts, made of 5000 and 6000 aluminium alloys. Material and structural analyses were performed using both finite element analysis and intensive destructive and non-destructive essays on specimens representing typical structural details of lightweight crafts. The effects of alloy combination, welding process, geometries non-linearities and stress concentrations on static mechanical properties and fatigue lives of the “as designed” and the “as built” structural details are evaluated and discussed, with the aim of improving the design and production under “safe life” vs. “fail safe” principles.

Keywords: Aluminium alloys, Structural details, Essays, Lightweight craft, Hammer-peening, Fatigue.

RESUMO: Este artigo apresenta os resultados de investigações preliminares sobre propriedades estáticas e dinâmicas de detalhes estruturais em lanchas rápidas, de estrutura leve, produzidas em ligas de alumínio das séries 5000 e 6000.
Foram realizadas análises estruturais usando o método dos Elementos Finitos e ensaios destrutivos e não-destrutivos em provetes representando detalhes estruturais típicos de lanchas rápidas. Os efeitos da combinação de ligas, do processo de soldadura, da geometria e da concentração de tensões nas propriedades estáticas e de vida à fadiga de detalhes, na configuração “como projectado” e “como produzido”, foram avaliados e discutidos, com o intuito de melhorar o projecto e a produção sob os princípios de “vida segura” vs. “falha segura”.

Palavras chave: Ligas de alumínio, Detalhes estruturais, Ensaios, Lancha rápida, Martelagem, Fadiga.

1. INTRODUCTION

The design philosophy of lightweight aluminium crafts is often focused on providing the structure with the necessary global, local secondary and local tertiary load carrying capacities. This approach sometimes overlooks the mechanics of the structural details involved in the overall geometry. Lightweight structures are already optimised to a relatively high level with in some cases reduced safety margins. A less accurate insight into the structural response to the applied loads, as result of the chosen structural details geometry and configuration, combined with complex non-linear behaviour induced by welding of two or more aluminium alloys, may lead to unexpected local or even global structural failure.

Additionally, loads such as high frequency dynamic pressures induced by slamming may represent the critical loads in an aluminium structure where failure due to fatigue is likely to occur. Despite having been considered in the design phase, the origin of failure in lightweight aluminium crafts does not often occur in primary or secondary structures, but rather in the structural details. The structural details inevitably induce localised stress concentration areas, which may be amplified by welding effects. The combined effects of geometric stress concentration and welding may cause short or long term failure, irrespective of whether their origins are from design errors or production defects.

The results of an investigation into the structural mechanics and associated failure modes (including fatigue) of structural details usually encountered in aluminium craft structures are presented. These structural details are associated with the non-watertight intersections between transverse frames, longitudinal stiffeners and bottom plate for which extensive surveys during construction showed as having significant production defects. Both the "as designed" and the "as built" structural details are evaluated using finite element analysis (FEA) for normal in-service loading conditions. The "as built" configurations were determined from ship surveys of typical defective geometries. Further, these typical details, made from 5000 and 6000 aluminium alloys, are studied in regard to their combined mechanical properties resulting from welding, by means of extensive non-destructive and destructive essays, in search of an insight to the resulting static and fatigue behaviour. Moreover, the effect of "hammer peening", as means of a "safe life" strategy, on the improvement of aluminium structural details' to fatigue effects is investigated.

The experimented fatigue lives for the structural details are compared to the design life of the craft and possible methods and materials and even methods of experimentation are discussed, with aim of improving production and provide guidance for further research in this matter.

2. DETAILS' GEOMETRY AND RESEARCH METHODS

The growing requirement for performance improvements and the simplification of production and maintenance practices have led to a progressive departure from the traditional conservative design philosophy usually associated with marine structures. This observation is based on the experience of evaluating the results of several structural surveys on in-service aluminium fast crafts, where it was observed some structural criticality in the vicinity of structural details such as those analysed here. These are non-watertight intersections between stiffeners (Figure 1) of external panels of the hull. This criticality - premature failure (collapse, tearing of welds and cracking) - was perceived to result from structural detail solutions developed both at a level of the design team and real solutions obtained from the production team.

Considering the aluminium alloys used in the construction of these crafts, as well as, the MIG welding technique applied, it was envisaged to get some scientific support for explaining the short run criticality (deformations, tearing of welds and fractures) and getting some insight on the long run criticality (fatigue behaviour). In this research work it was developed a battery of essays on models representative of the critical details, aiming to characterize the mechanical behaviour of the construction alloys, in order to perceive the importance of the various variables on the structure life span, as well as to propose techniques for its improvement and if possible, its correction.

This work involved the definition and development of simplified models of the details for destructive and non-destructive static and dynamic essays and FEA modelling for determining the stress levels and stress concentrations associated to different intersection detail solutions. The results from FEA were considered for loading definition in the fatigue tests.

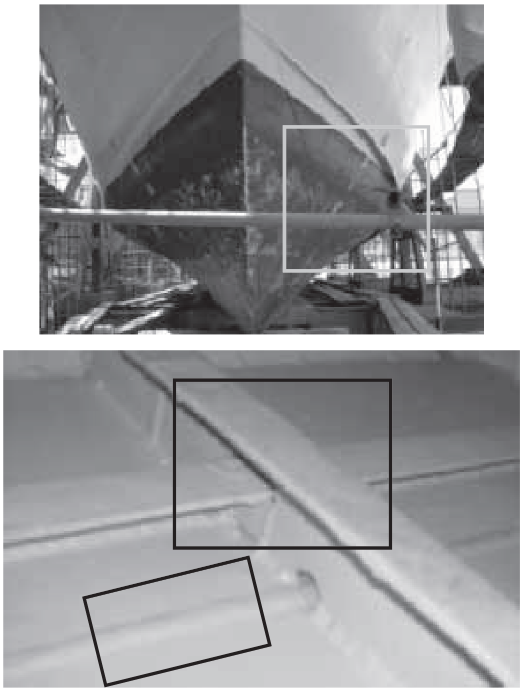


Fig. 1. Structural details under study.

3. FINITE ELEMENT ANALYSIS

3.1. FEA Model of the Structural Details

The advantage of using FEA to analyse structural details lies in the fact that important nonlinearities can be modelled without resort to experimental methods. The three sources of nonlinearity that are usually encountered are nonlinear material behaviour, nonlinear boundary conditions and geometric nonlinearity. In structural details it is geometric nonlinearities that are of most concern.

Figure 2 shows the global model geometry associated with the structural details investigated here. It is typical of the secondary structure of an allegedly optimised fast craft bottom structure. This model was kept unaltered and only the intersection structural detail was changed in accordance with each case.

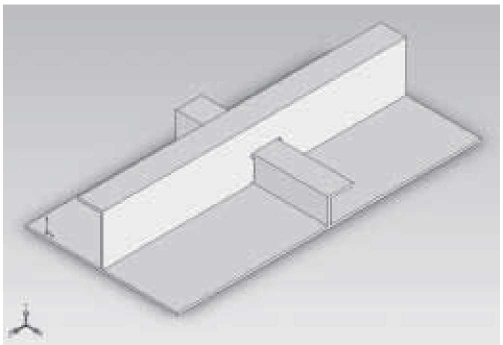


Fig. 2. Model geometry.

The model is a plate of 600x300x5mm reinforced by 100x50x5mm frames and 50x50x5mm longitudinals, as used on the bottom structure of a light craft. The material was defined as Aluminium alloy: 5083-H111 (AlMg4.5Mn) in the panels and 6082-T6 (AlMgSi1) in the stiffeners, but having an elastic stress-strain curve, whose characteristics are presented in Table 1.

Table 1. Aluminium alloys properties [1-5].

Properties	5083-H111	6082-T6
Density (kg/m3)	2660	2700
Young's modulus (GPa)	71	69
Tensile strength (MPa)	275-350	290-310
Yield strength (0,2%) (MPa)	125-145	250-260
Rupture strain (%)	12-22	6-10
Poisson's ratio	0.326	0.326
Vickers hardness (H_V)	76-91	95-105

These are asymmetric scantlings, which are representative of current cost effective shipyard production practices, such as those discussed by Salvado [6]. In order to identify the influence of geometry on mechanical response of the structural details, the welds and residual stresses were not modelled.

The finite element models were implemented in CosmosWorks with a three dimensional mesh of about 13900 elements using a 20 node quadratic brick element. In terms of definition of boundary conditions, the structures were restricted to fixed grillages, since we were interested in relative results between each detail case rather than absolute values. In fact, the rotational restraint due to welding is neither purely clamped nor simply supported, but lies somewhere in between with the stiffness dependent on parameters such as butt weld width and depth.

Four out of the five cases of intersection structural details discussed by Silva et al. [7] were analysed. Two "as designed" and two "as built" (Figures 3 and 4). The first structural detail (detail 1) consisted of a non-watertight intersection with a doubler fitted tripping bracket (or lug). The second structural detail (detail 2) consisted of a non-watertight intersection with an insert fitted tripping bracket. These details are widely recommended in the design codes as examples of good structural design practice. Front views of detail 1 and detail 2 are shown Fig. 3a) and b), respectively.

a) Detail 1. **b)** Detail 2.

Fig. 3. "As Designed" structural details.

Detail 2 represents an enhanced version of detail 1 but in essence represents the detail which gives a reasonable level of rotational restraint to the longitudinal stiffener and provides some compensation on the transverse stiffener (frame) web resistance area. Detail 1 has the advantage of being simpler and faster to execute, but it has the disadvantage of providing an overlapping area between the bracket and the frame web. This area will not be readily accessible for condition survey assessments.

In what concerns the expected structural response of these details under loading, it is expected that the bracket (or lug) has a major role in the connection performance by ensuring that the web shear forces are transmitted between the webs of perpendicular stiffeners. The welding of the longitudinal stiffener web is a complementary form of achieving the same functional role as the lug. The web opening geometry also influences the stress concentration field generated in the frame web.

Two "as built" structural details were analysed. The geometries of these structural details are a result of multiple vessel surveys in which the most frequent defective production geometries from the "as designed" details 1 and 2 were modelled.

Owing to the small dimensions of the stiffeners in small fast craft, it was observed that there were difficulties in the shippyard to produce the structural details "as designed". If the quality control is lax during the building of the vessel, then structural details such as those as presented in Figure 4 may be encountered. Details 1 and 2 "as built" in its version 1 (detail 3), shown in Figure 4a), consists in a non-watertight intersection where the tripping bracket has not been fitted, but the longitudinal web restraint and stress concentration relieve areas have been produced.

Details 1 and 2 "as built" in its version 2 (detail 4), shown in Fig. 4b), is also a non-watertight intersection without the tripping bracket fitted and without providing any longitudinal web restraint. This represents a very common production mistake in some shipyards, where quality control is only performed by the production personnel and there is a significant pressure to complete and deliver the vessel.

a) Detail 3. **b)** Detail 4.

Fig. 4. "As Built" structural details.

3.2. Loading Definition

In the case of designing structural details for high speed naval craft, it is the hydrodynamic impact loads that tend to govern the local loading criteria rather than global loads. These dynamic loads occur at frequencies higher than those associated with first order wave and motion induced loads, and are closer to the lowest natural frequency of the hull girder. Hydrodynamic impact loads may occur at any point along the length of the craft. The hydrodynamic impact loads are characterised by a short high-pressure pulse and a consequent response at all three structural levels; primary, secondary and tertiary.

The hydrodynamic impact loads such as bottom impact pressures due to slamming can be predicted by applying the rigid body motions of the monohull high speed craft to the structural details to obtain the local elastic response. This is a relatively common procedure, but it can lead to a more conservative design. For a more accurate and realistic model of the behaviour of the local structure, the impact loads should be determined by considering the hydroelastic response of the hull and introducing this global response into the analysis of the local structure.

The structural details under study are part of a secondary structure of a fast planning monohull craft with a displacement of 90 tonnes and a design speed of 22 knots. The seastate is characterised by a significant wave height of 1.25 metres. The load on the craft bottom was estimated according to "Rules and Regulations for the Classification of Special Service Craft", Lloyds Register of Shipping [8], as discussed by Silva et al [7]. From the calculation of several individual pressure contributions, a uniformly distributed total lateral pressure of 150 kPa was applied to the bottom plating for the FEA analysis.

4. DESTRUCTIVE AND NON-DESTRUCTIVE ESSAYS

In order to have a global understanding of the details' structural behaviour, we aimed to characterize the base alloys, butt-welded plates (as representative of the craft's bottom), "T" joints (representative of reinforced bottom) and bottom plate with stiffener intersections (full model in FEA and simplified model for essayed specimens).

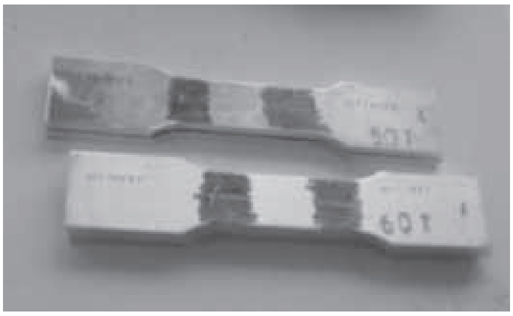
The flow of work involved the development and production of specimens for Non-Destructive Essays (NDE): Spectrophotometry (SPMTR), Visual Inspection (VI) X-Ray, Liquid Penetrant Inspection (LPI), and Destructive Essays (DE): Tensile (DET), Bending (DEB), Hardness (DEH), Fatigue (DEF). Table 2 presents each type of essay for the groups of specimens.

Table 2. Specimens developed for NDE/DE essays.

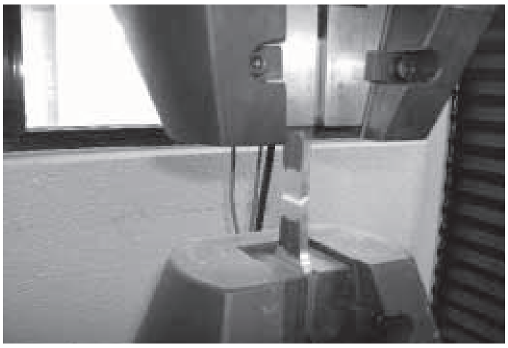
Group	Specimen Types	Tests & Essays	Number of spc
1	Base alloy 5083-H111	SPMTR, VI DET DEH	3
	Base alloy 6082-T6		3
2	Butt Welding (alloy 5083-H111) AW/HP	VI, X-Ray, LPI, DET, DEH	6
	Butt Welding (alloy 6082-T6) AW/HP		6
3	"T" Joint AW/HP	VI, LPI,DEB	6
4	Butt Welding (alloy 5083-H111) AW/HP	VI, X-Ray, LPI, DEF	4
5	"T" Joint AW/HP	VI, LPI,DEF	4

Even the filler metal alloys were controlled and characterized. The filler metal alloys were: 5183 and 5356. The use of each is done in accordance with of the location of the welded joint. In the welds between hull plates (5083/5083), where the effects of seawater are most expected, 5356 (AlMg5) alloy is used, due to its better corrosion behaviour. In all the internal welds, between plates 5083 and stiffeners 6082, free of sea water, the alloy 5183 (AlMg4,5) is used, which is more prone to corrode but has more mechanical strength.

A first group of specimens (Fig. 5) aimed to verify the mechanical properties of the base alloys, mainly compare them with theoretical values and values of the manufacturer. Thus the following essays were performed: chemical characterization by spectrometry and uniaxial tensile tests (UTT).



a) 5083-H111 and 6082-T6 specimens.

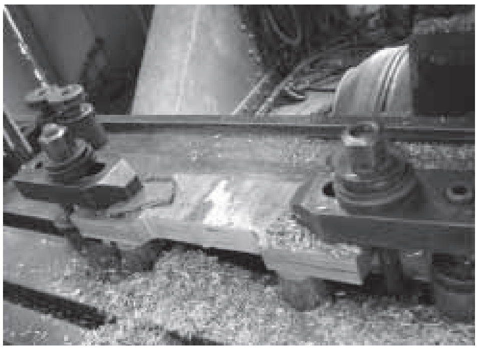


b) Uniaxial tensile test.

Fig. 5. Specimens: group 1.

A second group of specimens (Fig. 6) aimed to analyse the welded joint strength AW/HP, thus to analyse the combined effects of thermal and material welding influence on the structure strength as well as the mechanical properties variations caused by hammer-peening. These specimens consisted of butt-welded plates. After fabrication, quality control was assured by NDE essays, followed by UTT and hardness tests.

a) Two-side butt welding.

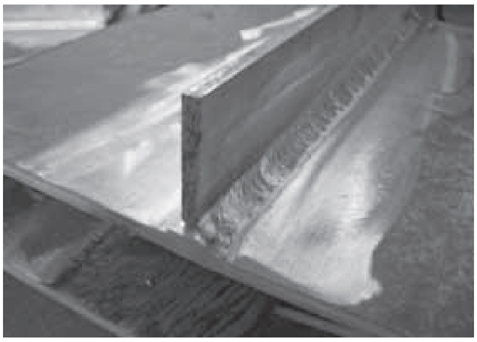


b) Machining of specimens.

Fig. 6. Specimens: group 2.

The third group of specimens (Fig. 7) aimed to analyse the bending strength (AW/HP) of a "T" welded joint made of a 5083-H111 alloy plate and a reinforcement of 6083-T6 alloy. Quality control was assured by LPI, followed by DE of pure bending and hardness.

a) MIG "T" joint welding.

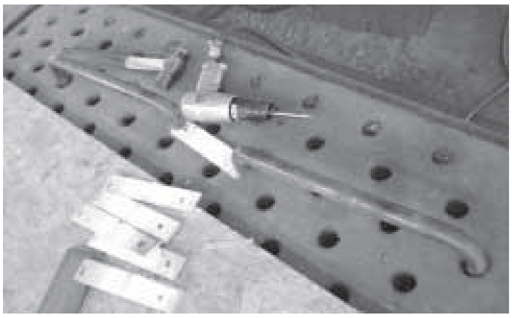


b) "T" joint specimen.

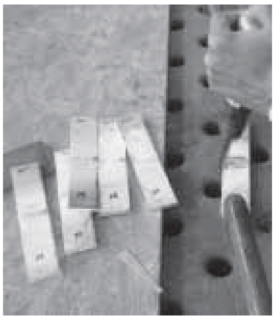
Fig. 7. Specimens: group 3.

The fourth group of specimens (Fig. 8) were designed for fatigue testing, in order to compare and analyse the fatigue lifes of weld toe hammer-peened (HP) and as weld (AW), not (hammer-peened) butt joints. These specimens are similar to the second one in geometry and materials, but half were HP and the other half AW. Quality control was assured by NDE essays, followed by DE of fatigue tensile tests.

The fifth group of specimens (Fig. 9) was designed for fatigue testing, in order to compare and analyse the fatigue lifes of HP and AW structural intersection of stiffeners and craft bottom plate. These were simplified models of the real structural detail and FEA models discussed above due to rig geometry and production constraints. The contribution of the frames to the fatigue behaviour (geometric stress concentration, residual stresses and heat affected zone (HAZ) was simulated by the two welding seams joining the frame to the craft bottom plate. Quality control was assured by NDE essays, followed by DE of fatigue tension.



a) Preparation for hammer-peening.



b) Hammer-peening.

Fig. 8. Specimens: group 4.

a) "T" joints before Hammer-peening.

b) Hammer-peening of "T" joints.

Fig. 9. Specimens: group 5.

The specimens were produced in the Arsenal do Alfeite (AA) shipyard. All the essays, were realized at AA and FCT/UNL. Fatigue tests were realized in the Instituto de Soldadura e Qualidade (ISQ).

5. FATIGUE LIFE AND HAMMER-PEENING AS A METHOD FOR ITS IMPROVEMENT

Through its life cycle, a marine structure is subject to several efforts and wearing. The cumulative effects of successive loading/unloading cycles may be amplified by the wearing promoted by harsh environment conditions such as that of salt water where marine structures have to operate, which are particularly aggressive. In this environment, several tests have shown that the fatigue life can be as much as one third of that allowed in normal air conditions[9]. Thus, craft design must consider these constraints such as the structure last the entire lifecycle without fail – "safe life design strategy" – or based on cost/benefit study incorporate structural redundancies in case one structural detail failure – "fail safe design" - as both strategies are called in aeronautical industry.

In this work we aim to study a technique for structural improvement of fatigue behaviour, which lies in the "safe life design" strategy: the hammer-peening. There are other techniques for structural improvement to fatigue, e.g. "burr grinding", TIG dressing, Laser Peening or Ultra-sonic Impact Treatment, that allow that structural details and welded joints to stand higher loads or last longer for the same level of efforts, basically by reducing the level of stress concentrations and/or the residual stresses, even when the structural details are constraints due to their complexity. These techniques may also be useful to ensure that a repair of a fatigue crack, especially in welded joints, will be lasting at least for the remaining useful life of the structure. All of these techniques have great variations in their effectiveness due to: some lack of standardization, different materials give different results, sensitivity to type of loading and sensitivity to operator skills.

The principle of hammer-peening is the introduction of compressive stresses by deforming plastically the weld toe. It is expected that these stresses will partially cancel the welding induced residual stresses. However, this technique is not applicable to highly loaded structures[9], (typically having nominal stress range 1,5 times the yield stress of the material).

The necessary equipment to produce hammer-peening is pneumatic or hydraulic hammer. If a pneumatic hammer is used, the usual parameters advised for aluminium are; a peen diameter between 5-12mm, an air pressure of 5-7bar and a frequency of 25-100Hz, thus generating an impact energy of about 5-15J[9]. The weight of the tool varies between 1,5 to 3,5kg. The hammer-peening parameters used in this work are listed in Table 3.

Table 3. Applied hammer-peening parameters.

Parameter (unit)	Value
Peen diameter (mm)	6
Air pressure (bar)	6,2
Frequency (Hz)	50Hz
Tool weight (kg)	1,8

For an effective treatment, it is necessary a rigorous positioning of the tip of the tool in the weld toe, in a way to cause the metal deformation. Fig. 10 illustrates the advisable positioning of the hammer.

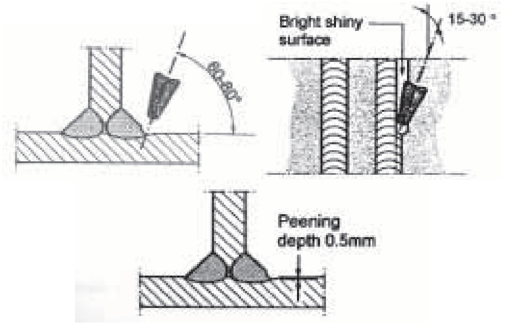


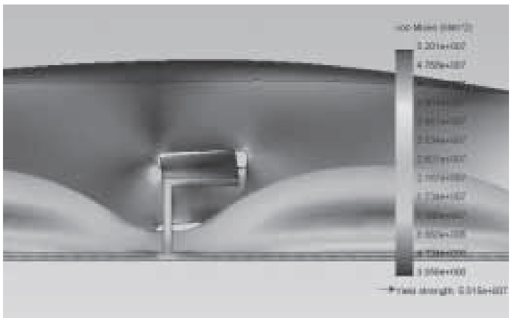
Fig. 10. Advisable positioning of the hammer [10].

The resulting groove must be smooth and shouldn't present marked individual indentations. Generally the depth of the weld toe indentation should be about 0,5mm with an acceptable range of 0,3-1mm. The velocity of displacement of the tool depends on the access, working position and type of equipment. A heavy and vibrating hammer will miss some zones, thus being necessary several passages until obtain a completely treated, regular smooth surface. A lighter and less vibrating tool allow for lower velocities of displacement, thus being more effective. In this work it was tried that to obtain a velocity of 50 to 100 mm per minute, similarly to a typical weld, to obtain the desired depth in one passage. The diameter of the peen influences the appearance of the treated surface. Generally, the smaller the diameter, the bigger is the probability of the weld toe to be indented itself and eventually eliminated. The work of hammer-peening must be permanently observed regarding hammer position, zone of actuation and uniformity of the surface and compared with a reference sample or reference photo [9].

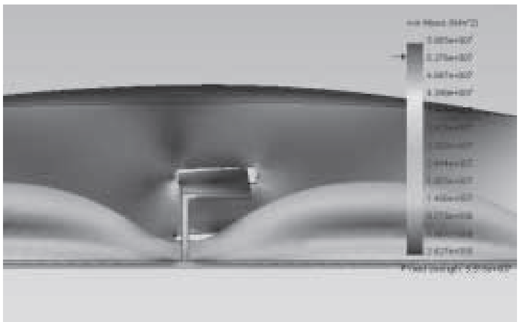
6. RESULTS AND DISCUSSION

6.1. Finite Element Analysis

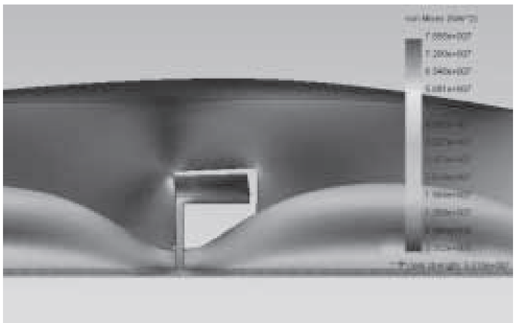
Figure 11 presents the von Mises stress contour results of the FEA for the details 1, 2, 3 and 4 presented in Fig. 3 and 4. Even considering that the chosen boundary conditions are not conservative ("fixed ends" against more conservative "simply supported"), different software as well as different finite elements and mesh were used, the results match quite well with those obtained by Silva et al [7]. The results were essentially considered and analysed away from the boundaries, were spurious results are expected, and focused on the intersection between longitudinals and frames.



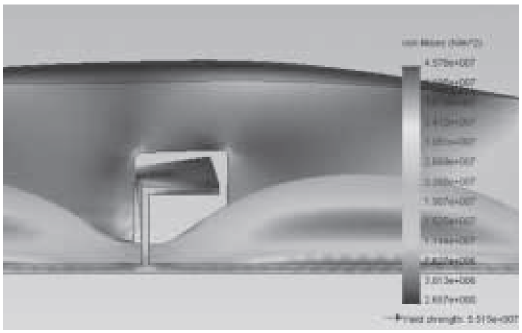
a) Detail 1.



b) Detail 2.



c) Detail 3.



d) Detail 4.

Fig. 11. FEA results.

After analysing the obtained results, it could be seen that the predicted tension are quite less than the yield strength of the two alloys, as expected, since the crafts are operating for seven years now in coastal Atlantic Ocean conditions without any reported major structural complaint.

Table 4 compares the global FEA results between the four structural details under analysis.

Table 4. Global results of FEA.

Parameter	Max Von Mises Stress (MPa) Max. Displacement (mm)
Detail 1	52 0,261
Detail 2	59 0,262
Detail 3	68 0,265
Detail 4	79 0,263

Comparing the four different detail solutions, it could be observed that detail 3 presents the lowest stress value, and detail 4 presents the highest stress value. Details 1 and 2 present values of the same magnitude both stress and displacement. Results of details 1 and 2 are in general in agreement with greater rigidity of those details and best structural continuity but rather more corners, thus complexity, than details 3 and 4. The results of details 3 and 4 agree with the fact that these are less rigid, but have higher stress concentrations factors.

Details 1 and 2 are often found in maritime transportation, however detail 1 is easier to produce specially if we are dealing with small scantlings as with small fast craft. However when it comes to hot spot analysis and design (HSD), the greater complexity of the details the higher the probability of appearing hot spots, even if with lower values of stress concentration factor (SCF), which may be the case of details 1 and 2. Details 3 and 4 are representative of poor shipyard practice, since they promote low rigidity structures (which in the case of marine structures are already quite flexible), high SCF details (at least higher than detail 2 according to Silva et al [7]) but less probability of appearing hot spots due to their simplicity.

In terms of "fail safe" vs "safe life" strategy approach to structural detail design, details 1 and 2 are more difficult and expensive to produce than detail 3 and 4, but the first are inherently more "fail safe" than the latter due to details 1 and 2 higher number of stress flow paths and structural continuity. In terms of "safe life" strategy, it is easier and less expensive to promote a life cycle without failures in details 1 and 2 than in details 3 and 4 since the latter would demand stress relievers or higher scantlings for the same number of cycles without failure.

In terms of the present work the higher value of stress obtained in detail 4 – 79MPa - was considered for purposes of fatigue testing design and calculations.

6.2. Spectrophotometry

For the spectrophotometry essay it was used an emission spectrophotometer Baiard Spectrovac 2000. The results are presented in Table 5, where the reference values given by standard EN 573-3: 2003 are also presented as maximum, except where a range is presented.

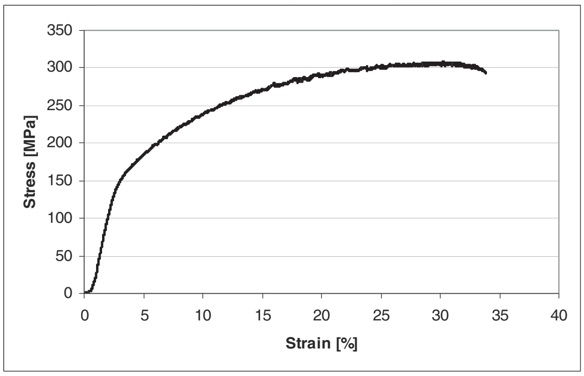
Table 5. Chemical characterization results.

Element	5083 St* % (m/m)	5083 % (m/m)	6082 - St* % (m/m)	6082 % (m/m)
Copper (Cu)	0,10	0,04	0,10	<0,02
Silicon (Si)	0,40	0,12	0,7-1,3	0,99
Iron (Fe)	0,40	0,30	0,50	0,20
Manganese (Mn)	0,40-1,0	0,53	0,40-1,0	0,50
Magnesium (Mg)	4,0-4,9	4,4	0,6-1,2	0,59
Chromium (Cr)	0,05-0,25	0,08	0,25	<0,01
Zinc (Zn)	0,25	<0,01	0,20	0,01
Titanium (Ti)	0,15	0,02	0,10	0,01

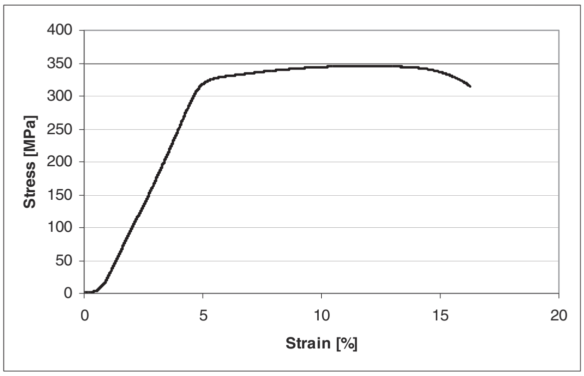
Analysing Table 5, it can be seen that the composition of the two essayed alloys are in agreement with the standard.

6.3. Uniaxial Tensile Testing – Base Metal (group 1 in Table 2)

The two alloys (5083-H111 and 6082-T6) tested in group 1 specimens have the global results of the overall essays presented in charts of Fig. 12.



a) 5083-H111 alloy.



b) 6082-T6 alloy.

Fig. 12. Stress/Strain curves for Metal Base (group1).

After analysing the values obtained from the rig computed values and charts in Fig. 12, it could be observed that the alloys have mechanical characteristics similar to those presented in general bibliography and summarized in Table 1.

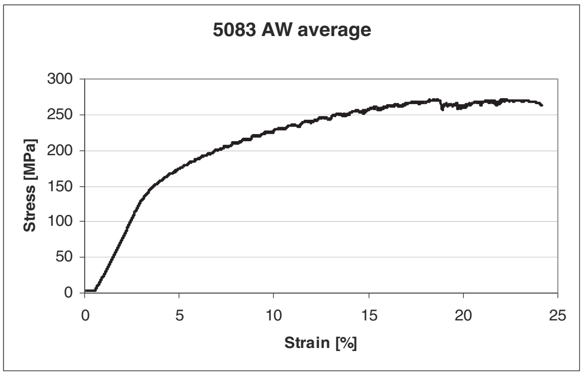
6.4. Uniaxial Tensile Testing – Butt Welded Specimens (group 2 in Table 2)

The results of the UTT on group 2 specimens, butt welded alloys AW/HP are now presented and discussed. All the specimens had the welds burr grinded in order to keep a constant transverse section. On the HP specimens the transverse section was reduced by 1mm in average due to the effect of the HP treatment. It is believed that the observed mechanical behaviour of the specimens is superior of that of specimens without burr grinding, once the variations of transverse section due to weld irregularities were quite smoothed. However, the effect of burr grinding on structural strength was not studied in this work. It must be clear that in naval construction not all welds are burr grinded. It may be that these results are slightly optimistic relatively to real butt weld on hull shell. On the contrary, it must be considered that there is negative contribution to mechanical strength given by burr grinding, which is the removal of material from the transverse section, thus reducing it. All in all, there may be cancellation effects from cross section area variation vs geometric stress concentrations in “raw” welds vs burr grinded welds that may give a similar resultant static mechanical strength.

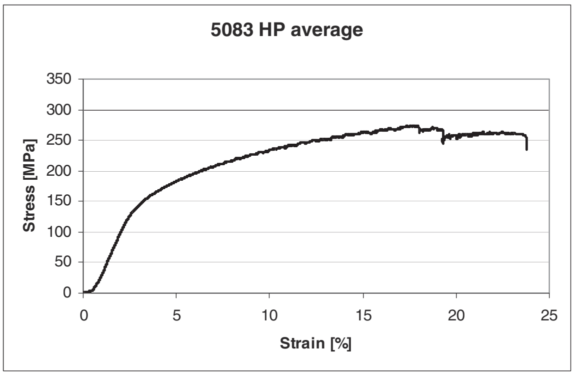
All the specimens made of 5083 alloy had their rupture along the weld seam, while the 6082 specimens broke 1-3 mm away from the weld toe, i.e. in the HAZ zone.

From the analysis of the results (charts presented in Figs.13 and 14) it was observed that the tensile strength is reduced by 44% in the 6082 AW and HP alloy and 10% in the 5083 AW and HP alloy. Though 5083 alloy is not thermally treatable, its HAZ does not present itself fragile, once all the specimens of this alloy broke on the weld seam. For the tensile strength values it was not observed significant variations between AW and HP specimens in both alloys.

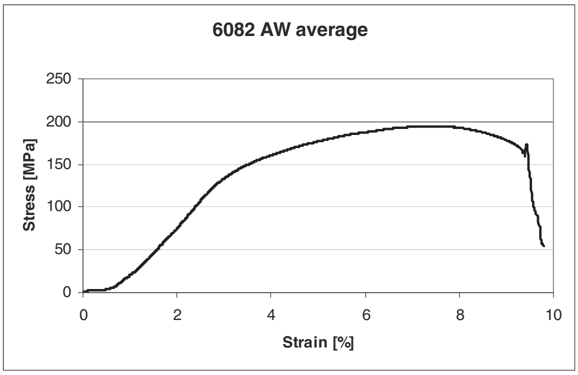
As far as rupture strain is concerned, there are significant differences relatively to base metal and between AW and HP specimens. There is a reduction of 46% for 5083 AW and 38% for 6082 AW and 54% for 5083 HP, and 55% for 6082 HP. It is observed a greater influence of welding on the resilience/tenacity of 5083 alloy than on its tensile strength and an even worse resilience/tenacity behaviour when hammer-peening treatment is applied. It is observed a great influence of welding on both the resilience/tenacity of 6082 alloy and its rupture stress and a worsen resilience/tenacity behaviour when hammer-peening treatment is applied. All in all, it was observed that hammer-peening worsen alloys’ mechanical properties. This may be related to the way the treatment was applied, because it was observed great irregular indentation on the surface of the HP specimens whose effects may had gone some millimetres below the surface. Thus, and even with the applied burr grinding, those effects were kept in the alloy crystalline structure.



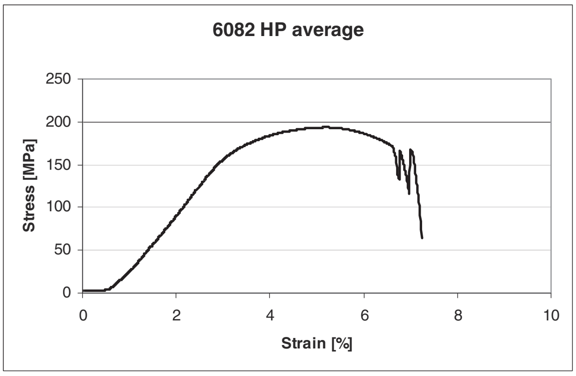
a) 5083-H111 AW alloy



b) 5083-H111 HP alloy

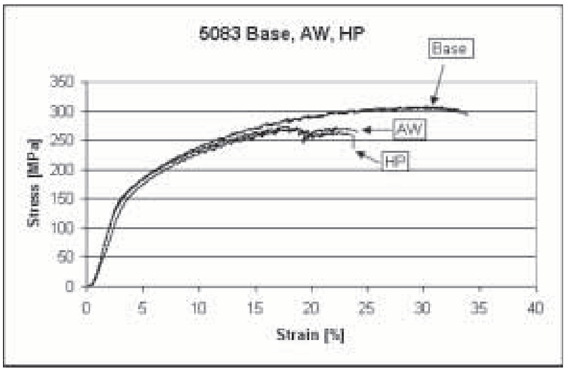


c) 6082-T6 AW alloy

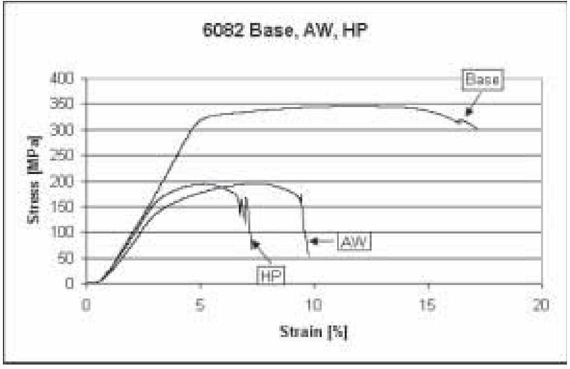


d) 6082-T6 HP alloy

Fig. 13. Stress/strain curves for Butt Welded specimens (group2).



a) 5083-H111 Base/AW/HP



b) 6082-T6 Base/AW/HP alloy

Fig. 14. Stress/strain curves comparing specimens of base metal (group1), AW and HP specimens (group 2).

6.5. Bending Test – (group 3 in Table 2)

The results of the DEB on group 3 specimens, "T" joints AW/HP are now presented and discussed. The aim of these essays was to compare the bending resistance of "T" joints AW and HP. Fig. 15 presents the results as bending moment (BM)/deflection curves. In none of the specimens occurred any type of fracture.

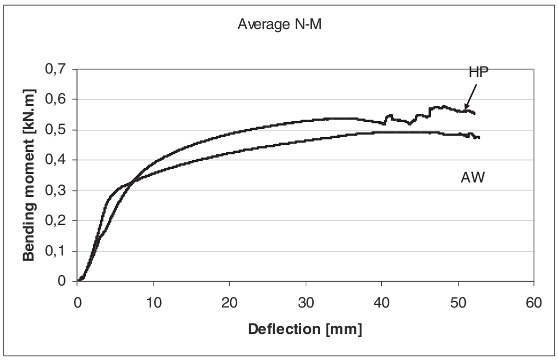


Fig. 15. BM/deflection curves comparing specimens AW and HP (group 3).

In general, it could be observed that AW specimens require up to 20% less BM than HP specimens. It seems that the plasticity introduced by hammer-peening causes higher bending resistance, especially seen as the outer fibres are becoming more loaded.

6.6. Hardness Test on Base Metal – (group 1 in Table 2)

The hardness test on the base metal was made to give reference values for the specimens under study, in order to perceive the extent of the thermal and mechanic treatments influence through the materials. The average of four essays gave Vickers hardness values of: 91 for 5083-H111 alloy and 118 for 6082-T6 alloy.

6.7. Hardness Test – (group 2 and 3 in Table 2)

Two measurements were made on the butt weld specimens (both AW and HP): one measurement through the weld, at 1mm from the surface, other measurement across the specimen thickness and along the weld toe. On the 6082 alloy it was made one more measurement at half thickness of the specimen through the weld.

On the 5083-H111 alloy specimens it was confirmed that hammer-peening increased the hardness of the area treated. Other fact observed is that hammer-peening seems to influence crystalline structure of the alloy at least up to 3mm in depth. In the 5083 AW specimen it was observed a sharp softening (about 30% relatively to the base material) of the material quite localized, the HAZ, while that couldn't be clear in the 5083 HP specimen. On the 6082-T6 alloy specimens it was confirmed that hammer-peening increased the hardness of the treated zone, including HAZ where under its effect. The analysis to the measurements across the specimens' thickness, on the weld toe, showed that in both alloys there is an increase in hardness for the HP specimens of about 10%.

Globally it was observed that the hardness of the 6082-T6 specimens was particularly affected by the welding process, especially if compared with the results observed for the 5083-H111 alloy. This result may be related with fact that the 6082-T6 alloy may be heat treated, thus being more sensitive to the weld effects. Each applied over-heating causes ageing, thus softening.

6.8. Fatigue Testing– (group 4 and 5 in Table 2)

The fatigue testing were performed in a high frequency magnetic resonance rig. The frequency was 110 Hz with stress ratio 0.3 (the specimen was always in tension). While the real structural detail is under lateral pressure, that was not possible to simulate on the fatigue testing. Thus, the best approach was to convert the actual loading into a tensile fatigue testing, where the maximum test load would generate the same stress value estimated by FEA for detail 4.

Analysing Table 6 and the specimens, it was observed that the first tested specimen ("T"joint AW) fractured on the sharp geometric transition between the shell plate and the weld seams simulating the craft frames. The fracture occurred at about 385e3 cycles, which is broadly one third of the craft life, usually considered as 1e6 cycles. This result reflects one of the common ways of crack propagation in real structures, by starting on the connection between the transverse frame and bottom plate (where this intersects the longitudinal), rather than on the continuous connection between the longitudinal stiffener and the bottom plate.

After removing the weld seams simulating the craft frames, the remaining "T" joints specimens were tested and all of them fractured on the circular hole, at about 200e3 cycles, where the test load and displacement was applied by the rig. It was also observed that hammer-peening did not change substantially the fatigue strength of the specimens.

As far as butt weld specimens is concerned, the results gave quite spread information: one of the HP specimens fractured in the weld after more than 1e6 cycles of loading. As this as the only specimen to fracture in this zone, it could be due to some internal defect in the weld, since the second HP specimen had infinite life. One of the AW specimens fractured on the circular hole, at about 400e3 cycles, where the test load and displacement was applied by the rig, confirming this zone as drivers of the fatigue strength of the specimens, rather than the weld zone. The two remaining specimens (one AW and one HP) had infinite life, but for half the load.

Table 6. Results from fatigue tensile testing.

Specimen		Section Area [mm^2]	Test Load [kN]			Nr of Cycles	Fracture
		Area	Min.	Max.	Range		
"T" joint	AW	270,00	5,10	17,00	11,90	385000	(a)
	AW	270,00	5,10	17,00	11,90	225100	(b)
	HP	270,00	5,10	17,00	11,90	184900	(b)
	HP	120,00	2,30	7,56	5,26	243300	(b)
Butt Welding	AW	270,00	5,10	17,00	11,90	440040	(b)
	AW	120,00	1,15	3,80	2,65	5043600	(c)
	HP	120,00	1,15	3,80	2,65	6168000	(c)
	HP	120,00	2,30	7,56	5,26	1152800	(d)

(a) transition between frame and shell; (b) failed in grips (c) unbroken; (d) weld toe

7. CONCLUDING REMARKS

After analysing all the data produced in this work it could be concluded that:

- In general the specimen welds are of good quality, both in terms of porosity (NDE's) and mechanical strength (shown by UTT and DEB);
- The alloys used on the crafts have properties within the values expected from several references;
- The butt weld reduced the break strength of the alloys as much as 10% for 5083-H111 and 44% for 6082-T6, and hammer-peening treatment did not change noticeably this behaviour;
- The rupture strain is significantly reduced by welding process; about 40% for 6082-T6, about 50% for 5083-H111, relatively to metal base;
- Hammer-peening worsen the rupture strain limits of the specimens; about 55% for the two alloys;
- Hammer-peening increased the bending strength of "T" joints of about 20%;
- Hammer-peening increased the hardness of the 5083-H111 HP specimens up to 30%. If applied in HAZ, hammer-peening almost eliminates the softening promoted by local welding overheating;
- Welding overheating, reduces the hardness of both alloys, but 6082-T6 alloy is especially affected;
- Fatigue resistance is driven stress riser details. The difficulty of producing a smooth hammer-peening treatment due to the random nature of the operator actuation, may induce localized stress risers;
- The stiffener intersection details are particularly critical to fatigue resistance.

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REFERENCES

[1] Algroup alusuisse fabricated products, Technical Data Sheet – PERALUMAN® - 460, January 2000 edition.

[2] Product Range, Alumeco, 2003/2004

[3] Algroup alusuisse fabricated products, Technical Data Sheet – ANTICORODAL® - 110, January 2000 edition.

[4] Matias, C., "Estudo do comportamento de Ligas de alumínio para Construção Naval: Abordagem Centrada nos Métodos para Melhorar o Comportamento à Fadiga de detalhes Estruturais" (in Portuguese), Dissertação de Projecto II, FCT/UNL, DEMI, (2008), Lisboa, Portugal.

[5] Martins, N., "Estudo do Comportamento de Ligas de Alumínio para Construção Naval: Abordagem Centrada na Influência dos Parâmetros de Soldadura nas Características Mecânicas das Estruturas" (in Portuguese), Dissertação para Mestrado, FCT-UNL, (2008), Lisboa, Portugal

[6] Salvado, F.C., Considerações sobre o projecto de Lanchas Rápidas, Seminário "Projecto, Construção e Manutenção de Navios" (in Portuguese), (1998), Escola Naval

[7] Silva, P.P., Mateus, A., Witz, J., Pereira, C., "Performance Enhancement of Structural Details in Aluminum Crafts", (2004), PRADS2004 9th International Symposium on Practical Design of Ships and Other Floating Structures, pp. 790-797, Lübeck-Travemünde, Germany

[8] Lloyd's Register of Shipping, Rules and Regulations for the Classification of Special Service Craft, Lloyd's register of Shipping, (1999), London

[9] Maddox, S., Review of fatigue assessment procedures for welded aluminium structures, (1999), The Welding Institute; doc. 688/1999

[10] Haagensen, P. Maddox, S., IIW Recommendations for Weld Improvement by Burr Grinding, TIG dressing and Hammer Peening for Aluminium Structures, (1999), IIW Commision XIII.