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Load shortening characteristics of marine grade aluminium alloy plates in longitudinal compression

Abstract

This study presents detailed and rigorous numerical analysis for a parametric series of unstiffened aluminium plates typical of those used in lightweight ships and equivalent thin walled stiffened structures. The study is undertaken with a nonlinear finite element analysis procedure using ABAQUS. The strength behaviour of the plates under a progressively increasing longitudinal in-plane load are shown to be affected by a number of parameters including the alloy, geometric imperfection shape, heat affected zone distribution, level of heat softening and residual stress distribution. The comparative influences of these various factors, some of which are specific to welded aluminium structure, are explored to determine which must be accounted for in the development of a parametric series of design curves.

1. Introduction

Welded aluminium alloy plate has become an established primary hull structural material used for medium to high speed ships mostly operating as commercial passenger craft. The size and operational extent of aluminium vessels has continued increasing over the last twenty years and the potential for aluminium as a viable material for high speed, ocean going ships is continuing to be explored. This is exemplified by the recent construction of a 127 metre aluminium trimaran commissioned as part of the US Navy Littoral Combat Ship (LCS) program. Aluminium is usually chosen as an alternative to normal or high tensile steel; the advantages including a high strength to weight ratio, good resistance to corrosion and comparable ease of manufacture.

Operational requirements for large high speed craft such as the LCS include exposure to extreme and potentially hostile deep sea environments for significant periods. This has a corresponding influence on strength requirements during the design process, where limit state approaches can be employed to ensure a lightweight scantling specification. Therefore the design of such vessels requires structural prediction techniques capable of producing a light structure with high confidence in its strength and safety.

In light of these continuing advancements in aluminium shipbuilding, there is general recognition that a better understanding of the characteristics of welded aluminium alloy structure is required [1]. This study presents detailed and rigorous numerical analysis of unstiffened aluminium plates using the nonlinear finite element method (NLFEM). ABAQUS, a general purpose finite element software with nonlinear capabilities, is used throughout [2]. The influences of the geometric and material factors specific to welded aluminium structure are explored. The study shows that a rigorous finite element approach is required to adequately capture the influence of heat affected zone, residual stress and geometric imperfections.

2. Background

Shell and deck plating usually comprises between 65% and 85% of the midship cross section area of the hull girder. For the purposes of structural analysis, they are often treated as individual unstiffened elements, bounded by stiffeners on all four edges. Each plate element must adequately fulfil a number of roles within the ship structure. These can be broadly split into local and global functions. Local functions are usually considered to fulfil service limit states, such as withstanding local hydrodynamic pressure loads. The global function of the plate as an integral part of the continuous hull girder is important for ultimate limit state analysis.

Theories to predict the strength of a flat plate under various load combinations have been studied extensively for over 120 years, with the first theoretical examination of the plate buckling problem by Bryan [3]. Since then the instability of plate elements under a wide variety of loading conditions has been extensively studied using numerous different experimental, theoretical and numerical approaches. A thorough review of the historical development of classical plate strength theory is given by Rhodes [4].

The fundamental research into plate strength and stability has driven the development of modern design guidance, which usually aims to minimise the weight of a structure whilst maintaining sufficient local and global strength under prescribed load criteria. Well established design methods, such as the Johnson-Ostenfeld parabola [5], adapted theoretical work into empirical equations suitable for allowable stress methods. Extensive physical and numerical tests have complemented theory, developing a better understanding of real plate behaviour and thus improving practical design guidance.

More recent plate strength research has been undertaken to develop limit state design approaches, which requires a more thorough consideration of the ultimate capacity of the plate under specific load scenarios. Modern statutory guidelines, such as the Eurocodes [6,7], have extended design formulas to encapsulate numerical and physical test data and present a more rational approach to design. They derive the plate strength as a limit state criteria, where the strength is judged directly against the load at the ultimate, accidental, fatigue and serviceability level [5]. There are many formulas developed to predict the ultimate strength of a long plate under uniaxial compression; only examples commonly used in the marine industry and of particular relevance to this study are reviewed here.

Possibly the most commonly quoted empirical formula used in the marine industry to estimate the strength of simply supported steel plates under longitudinal compression was proposed by Faulkner [8]. The formula has been found to correlate well with test data from various steel plate experiments [9]. The formula includes the effects of residual stress and distortion, albeit implicitly, and provides a good fit through test data derived from steel plates constructed under normal manufacturing conditions.

The Johnson-Ostenfeld parabola is used by classification societies [10,11] and is a correction of the theoretical linear elastic buckling formula. It disregards the margin between buckling and collapse for slender plates, assuming that if the elastic buckling stress is less than half the yield stress, the critical stress equals the former. For stockier plates an empirical correction based on the same

principles as the effective width concept is employed. The formula is conservative for slender plates because it determines the ultimate strength as equal to the elastic buckling strength. This gives more of a serviceability limit than an ultimate limit and is considered an acceptable conservatism to impose for classification requirements and where other stress based criteria may also be imposed.

Eurocode 9 [7] was originally developed for the design of buildings and civil engineering works made from wrought and cast aluminium alloys, but is equally applicable to marine grade aluminium plates. The code is extensive and supersedes British Standard BS8118 [12]. It defines the ultimate strength of a plate under uniform uniaxial in-plane compression in the form of a limit state.

Paik and Duran [13] developed a design formula specifically to define the ultimate strength of flat rectangular unstiffened aluminium plates including the effects of the HAZ. The formulation is based on regression of results from NLFEM analyses of plates with material properties equivalent to 5083-H116, 5383-H116 and 6082-T6 aluminium alloys. An account is also made for average geometric imperfections.

The four empirical methods are compared in Figure 1. Additionally, some relevant data from aluminium plate tests carried out by Mofflin [14] are included in the diagram. The Eurocode 9 and Paik regression formula plots are derived for a typical 5083-H116 aluminium alloy plate of breadth 400mm, length 1200mm and with a HAZ breadth of 25mm.

The plot shows that the general relationship between strength and slenderness are universal across methods. In the intermediate slenderness region there is a spread between results. Paik and Duran's formula forms the lower bound whilst Eurocode 9 gives an upper bound. This is interesting as these are the two aluminium specific methods compared. Paik's method is generally closer to the experimental data. In the high slenderness region the Johnson Ostenfeld parabola does not take into account post buckling behaviour and thus gives a highly conservative solution. The other methods correlate closely, demonstrating that, for very thin plates, collapse behaviour is dictated by geometry rather than material properties.

Figure 1 – Comparison of empirical methods to predict aluminium plate strength

The code formulations and empirical formulae only predict the ultimate strength of the plate. A more complete view of plate strength under compression are given by load shortening curves, which show the nonlinear relationship between strength and end shortening (or global strain) up to and beyond buckling and collapse of the plate. Load shortening curves are particularly useful in simplified approaches to predict the nonlinear behaviour of a structure under global load. They can be used to define the effective stiffness of the plate element at any given end strain. An example of this application is in the simplified progressive collapse method originally defined by Smith [15], which is an established method to determine the ultimate longitudinal bending strength of a hull girder.

Load shortening curves for a parametric series of steel plates, based on extensive physical and numerical test data from a variety of sources, are presented by Smith et al. [9]. The curves are presented as a function of the plate slenderness ratio (β), which is defined as:

$$\beta = \frac{b}{t} \sqrt{\frac{\sigma_0}{E}} \quad 1$$

where b is the plate width between supports, t is the plate thickness, σ_0 is the yield or proof stress of the material and E is Young's modulus. The curve series are presented for plate slenderness' between 1.0 and 4.0 and for three levels of geometric imperfection. The effects of welding induced residual stresses are also included.

The plate load shortening curve datasets form a crucial part in defining stiffened element behaviour in the Smith progressive collapse method [16]. Recently, an extension of the progressive collapse method to aluminium structures has been proposed [17]. This requires the development of specific load shortening curve datasets for marine grade aluminium alloy plates which can then be used in a semi analytical method to predict stiffened panel strength [18]. As is elaborated in this paper, consideration of the factors specific to welded aluminium alloy plate must be accounted for within these parametric curve datasets.

3. Properties of Marine Grade Aluminium Alloy

It is important to properly define the material properties in NLFEM of shell structures. Therefore, the following review of the specific properties of marine grade aluminium alloy provides the basis for the rigorous numerical analysis carried out in this study.

3.1. Alloy Composition

Aluminium is obtained in fused form from the mineral bauxite, and an electrolysis process is then used to separate the element from the compound. The base material is then usually alloyed with small quantities of elements including magnesium, silicon, manganese, zinc, copper and titanium. The alloying process generally increases the strength of aluminium and can also increase corrosion resistance, reduce the melting point and change the ductility of the metal.

The grades of aluminium alloys typically used in the marine industry are the 5xxx and 6xxx series. These both include magnesium as an alloying element, which increases the resistance of the material to corrosion from seawater. Other alloys have been used in the past for marine

construction, including several in the 2xxx and 7xxx series. However, these alloys are highly susceptible to corrosion in a salt water environment. Even with specifically designed coatings, craft built from 2xxx and 7xxx alloys suffered from severe corrosion and fatigue problems [1].

5xxx series aluminium has Magnesium (Mg) as the main alloying element and may also comprise a significant amount of manganese. 5xxx series alloys are strengthened by work hardening. Alloys of this series are the most commonly used material in aluminium ship construction. The alloy is weldable, formable, highly corrosion resistant, has high weld zone ductility and high strength. Various variations in strength values exist between alloys in the 5xxx series. The most commonly used 5xxx alloy in aluminium hulled ships is 5083-H116.

Aluminium alloys of the 6xxx series use Magnesium and Silicon as the main alloying elements. These agents form magnesium silicide and the alloy is therefore heat treatable and can be extruded into complex shapes. 6xxx series alloys are mainly used in shipbuilding to form extruded parts such as beams, stiffeners and bars but are also used in sheet or plate form. In general, the 6xxx series alloys have less fracture toughness compared to the 5xxx series. These alloys also have variations in strength between the various tempers. Two commonly used 6xxx alloys in the marine industry are 6061-T6 and 6082-T6.

3.2. Stress-Strain Relationship

Due to variations in the composition of the various alloys of aluminium, the modulus of elasticity varies, but in general it can be taken as 70GPa. This is approximately one third of the stiffness of steel, which has an elastic modulus of around 210GPa. As can be seen in Figure 1, there is no clear yielding point for aluminium. As a result of this, the yield point is usually assumed to be the stress corresponding to the point when the plastic component of strain is 0.2%. This point is otherwise known as the 0.2% proof stress.

The Ramberg-Osgood equation [19] has been found to give a close approximation to actual alloy stress-strain curves. It is defined as:

$$\varepsilon = \frac{\sigma}{E} + 0.002 \left(\frac{\sigma}{\sigma_0} \right)^n \quad 2$$

where n is an exponent or “knee factor” defined either by physical tests or using established approximation techniques [20]. As the value of the exponent rises the stress-strain curve flattens out and more closely represents the elastic perfectly plastic approximation. Values of the exponent for the alloys considered in this study from recent literature are presented in Table 1. It is notable that there are significant uncertainties in the knee factors for all alloys considered. For this study, exponents of 15 for 5083-H116 and 30 for 6082-T6, are used.

Table 1 - Knee Factors for Ramberg Osgood relationship – comparison of literature values

	Mazzolani [20]	Collette [21]	Paik [22]	Zha [23]*	US D.O.D. [24]
5083-H116	27	12	15	14-21	
5383-H116	23		15		
6061-T6	45				21
6082-T6	47	30	15	30-46	

* Increasing exponent for increasing plate thickness

Example stress-strain relationships are shown in Figure 2 for 5083-H116 and 6082-T6 alloys. It can be seen from these two figures that the 5xxx series alloys depart noticeably from the linear elastic response at about 70% of the yield stress. The 6xxx series alloys have a stress-strain curve more closely approximating the elastic perfectly plastic approximation. The bilinear approximation provides a better correlation at high strain levels but cannot replicate the rounded portion of the curve before the 0.2% offset proof stress point.

Figure 2 – Aluminium alloy 5083-H116 (left) and 6082-T6 (right) stress-strain relationship

3.3. Heat Affected Zone

The material properties of a welded aluminium alloy plate are affected by two significant phenomena associated with the welding process. Welding inputs heat non-uniformly across the plate during panel fabrication; the heat softens the material adjacent to the weld, causing a heat affected zone, and also imparts internal residual stresses over the plate area. These material imperfections have separate physical causes, but both are caused by welding. The idealised heat affected zone used for design purposes is described here whilst the residual stress pattern is detailed in the next section.

The heat affected zone (HAZ) describes the area of plate weakened by the welding process. HAZ occurs at the edges of plates adjacent to fillet welds for stiffeners (rolled plate) or butt welds for adjacent plating (extruded plate with stiffeners). The formation of HAZ is due to different metallurgical processes for 5xxx and 6xxx series alloys.

5xxx series alloys are strengthened by work hardening in the milling process. Subsequently, the high heat of fusion welding raises the temperature of material that is close to the weld above the re-crystallisation temperature, removing the work hardening and leaving the material in the weaker annealed (O) state.

6xxx series alloys are heat treated to increase their strength. The heat generated during welding causes the magnesium silicide precipitates, which provide extra strength in the alloy, to turn back into solution in the weld itself. Further away from the weld the precipitates grow in size, which reduces the local alloy strength by nearly half.

The mechanical strength properties of an aluminium plate gradually decrease close to a welded connection, reaching a minimum at the centre of the weld. Because the temperature during welding decreases with increased distance from the weld, the material properties in the HAZ region also change with distance from the weld. It is difficult to accurately model the correct material property throughout the weakened zone in numerical analyses. Usually the HAZ is assumed to have constant representative material properties over a defined breadth of plating to approximate the actual material properties. Figure 3 shows an example sketch from Hill [25] of the design approach to represent the HAZ breadth. For a stocky plate the properties may also be different through the plate thickness (Figure 4).

Figure 3 - Effective HAZ breadth [25]

Figure 4 – Through thickness HAZ formation [26]

The HAZ width can be established by testing the hardness of the area close to the boundaries of welded plates. Some early experiments of 6xxx series plates were carried out by Hill et al [25]. Normally, a simplification of the HAZ distribution is made by assuming a constant reduced elastic limit zone. The size of this representative zone is less than the actual affected area, as shown in Figure 3. Mazzolani [20] suggests a 25mm representative HAZ, based on experiments. Zha and Moan [23] and Paik and Duran [13] also propose a 25mm HAZ breadth. In addition, Zha tested HAZ breadths of 12.5mm. Both 25mm and 12.5mm HAZ breadths are used by Collette [21] in numerical analyses of aluminium box sections.

BS8118 [12] and Eurocode 9 [7] include explicit formulas to estimate the HAZ width. Both codes give HAZ breadth as a function of the plate/stiffener thickness to include the effect of the temperature distribution in different thickness material. The following formulas given are valid for fillet welds applied to 5xxx or 6xxx series alloys.

BS8118 defines the HAZ breadth as:

$$z = \alpha \eta z_0 \quad 3$$

where α and η are modifying factors to account for the material being at an elevated temperature and increased heat build-up during the welding process. Both values can be taken as 1.0 for the purposes of this study, consistent with the approach of Kristensen and Moan [27]. z_0 is defined as:

$$z_0 = \min \left(20 + \frac{t_A}{3}, \frac{3t_B^2}{t_A} \right) \quad 4$$

where t_B and t_C are the thickness of the thickest and thinnest element respectively and t_A is the lesser of $0.5(t_B + t_C)$ and $1.5t_B$.

Eurocode 9 gives HAZ breadths for ranges of the average material thickness as follows:

$$\begin{aligned} 0mm < t_p \leq 6mm : & \quad b_{HAZ} = 20mm \\ 6mm < t_p \leq 12mm : & \quad b_{HAZ} = 30mm \\ 12mm < t_p \leq 25mm : & \quad b_{HAZ} = 35mm \\ 25mm < t_p : & \quad b_{HAZ} = 40mm \end{aligned} \quad 5$$

The code values are shown in Figure 5 for a range of plate thicknesses. The plate is assumed to be of equal thickness to the attached stiffener/plating. It can be seen in Figure 5 that Eurocode 9 predicts a larger HAZ breadth than BS8118 for all usual plate thicknesses. For the range of plate thicknesses considered in this study the codes give HAZ breadths in the region of 25mm.

Figure 5 - Extent of HAZ for a range of plate thickness and specification codes

The reduced proof strength in the HAZ can be approximated by a knock down factor. Factors are specified by classification societies. Knock down factors are also presented in a number of recent papers.

Material properties in the HAZ are usually determined by testing. Specimens from a standard butt weld are cut, normally either 50mm or 250mm in length. Most data has been collected with 250mm specimens and this has led to anomalous results because the HAZ constitutes a smaller percentage of material in these larger test pieces. Data from numerous sources is presented in Table 2, partly reproduced from SSC-452 [1].

The assumed heat affected stress strain curves for 5083-H116 and 6082-T6 as used in this study are shown in Table 2. The curves are based on strength reductions of 67% for 5083-H116 and 53% for 6082-T6 [7]. The knock down factor can also be applied to the Ramberg-Osgood exponent [21,23].

The knock down factor can also be applied to the Ramberg-Osgood exponent [21,23]. Based on the typical values given in Table 2, a knockdown factor of 0.67 and 0.53 were applied to the 5083-H116 and 6082-T6 material models respectively. The resulting stress-strain curves are shown in Figure 6.

Table 2 - HAZ Properties

		<i>Collette [21]</i>	<i>Paik and Duran [13]</i>	<i>Zha and Moan [23]a</i>	<i>DNV [11]</i>	<i>Alcan [28]</i>	<i>Kissell and Ferry [29]</i>	<i>ABS [10]b</i>
5083-H116	σ_{0HAZ}	144	144	144	125	125	115	165
	$\sigma_{0HAZ}/\sigma_{0.2}$	0.67	0.67	0.67	0.58	0.58	0.53	0.77
5383-H116	σ_{0HAZ}	-	154	-	145	145	-	165
	$\sigma_{0HAZ}/\sigma_{0.2}$	-	0.7	-	0.67	0.67	-	0.77
6061-T6	σ_{0HAZ}	-	-	-	115	-	105	103-138c
	$\sigma_{0HAZ}/\sigma_{0.2}$	-	-	-	0.48	-	0.40	0.40-0.53
6082-T6	σ_{0HAZ}	138	138	138	115	-	-	-
	$\sigma_{0HAZ}/\sigma_{0.2}$	0.53	0.53	0.53	0.44	-	-	-

^a:Based on DNV data, ^b:Values for butt welded alloys, ^c:Lower value for material under 9.5mm thickness

Figure 6 – Comparative HAZ material properties for 5083-H116 and 6082-T6 aluminium alloys

3.4. Residual Stress

Residual stress is the term used to describe the self-equilibrated internal stresses present in otherwise unloaded structural elements. Internal localised stress patterns are created when some or all areas of a structural member undergoes physical or thermal induced deformation, and is subsequently prevented from returning to its previous non deformed state. This creates a permanent, inhomogeneous deformation field in the structural member.

Residual stress fields are generated in most metal structures and manufactured parts during construction [30]. For ship structure the most significant cause of residual stress is the welding process during fabrication [1]. As it cools following a weld pass, the liquid weld bead at the joint is resisted from contracting by the bulk of the parent material. This causes tensile residual stresses to form within and near to the weld, and equilibrating compressive stress fields in the unheated plate region away from the weld joint. A typical idealised residual stress pattern for weld about the plate edges is illustrated in Figure 7.

Figure 7 - Idealised residual stress distribution with weld along all four edges of the plate [5].

To ensure equilibrium over any plate cross section a relationship between the residual stress and the width of the tensile stress field is:

$$b_t = \frac{\sigma_{rcx}}{2(\sigma_{rcx} - \sigma_{rtx})} \quad \text{and} \quad a_t = \frac{\sigma_{rcy}}{2(\sigma_{rcy} - \sigma_{rty})} \quad 6$$

where all symbols are as shown in Figure 7. For a steel plate the tensile residual stress zone should usually be considered to be equal to or just less than the material yield stress. However, due to the heat induced softening produced near welded aluminium joints, the corresponding tensile residual stress for aluminium is closer to the HAZ proof stress. This assumption has been validated by residual stress measurements taken in a recently conducted aluminium panel experimental programme [31], which indicate tensile residual stresses well below the parent metal strength and closer to the assumed HAZ strength.

The width of the tensile zone depends on the level of heat input during welding. An empirical approach to estimate the compressive residual stress of steel plates is given by Smith et al. [9], which can then be used in combination with Eq. 6 to calculate the tensile residual stress zone:

$$\frac{\sigma_{rcx}}{\sigma_0} = \frac{\sigma_{rcy}}{\sigma_0} = \begin{cases} -0.05 & \text{slight} \\ -0.15 & \text{average} \\ -0.30 & \text{severe} \end{cases} \quad 7$$

This expression is based on survey data from predominantly steel test pieces.

When applied to typical aluminium geometry, Eq. 7 can result in specifying quite large tensile zones, much greater than the corresponding HAZ width. The discussion regarding HAZ width has concluded that the heat input during welding usually conducts a certain distance from the weld joint. Because residual stress is also formed by heat input, this suggests that the tensile residual stress zone and HAZ can be assumed to cover the same width.

A recent Ship Structure Committee study [31] provides some evidence to validate the assumption of equal HAZ and tensile residual stress zone width. The study measured residual stresses in aluminium panels using a hole drilling procedure, with carefully positioned gauges to capture the strain released at the test points. The tensile stress region is shown to be of similar magnitude (approximately 25mm) to the expected HAZ breadth.

4. Results

An aluminium plate load shortening relationship is predominantly a function of beta, but will also be influenced by boundary condition, imperfection amplitude, material properties, imperfection shape, residual stress, HAZ location, relative HAZ width and aspect ratio. These parameters are now examined in turn to assess their relative influence.

4.1. General Parameters

The following analyses of plate strength present the influence of multiple parameters including alloy type, geometric imperfections, HAZ and residual stress. To ensure standard comparable results, a “base case” definition of each parameter is required to be used as the default when that parameter is not of direct interest. Therefore, unless otherwise stated, the “base case” parameters are as follows:

- 1200mm (a) x 400mm (b) dimensioned plates,
- Simply supported boundary condition,
- HAZ width: $b_{HAZ} = 25\text{mm}$ (HAZ ratio: $HR = 0.125$),
- Longitudinal residual stress with tensile region equal in width to the HAZ and with initial stress of $0.95\sigma_{0HAZ}$,
- 3 mode imperfection pattern Fourier series (Eq. 12),
- Average imperfection amplitude ($w_{0pl} = 0.1\beta^2t$),
- 5083-H116, 6082-T6 Ramberg Osgood material properties or 245MPa elastic perfectly plastic steel
- Mesh element length = 15mm.

Further information detailing the reasoning behind the choice of each standard parameter is given in the following discussion.

Load shortening curves are normalised with respect to the 0.2% proof stress (aluminium) or yield stress (steel) of the material (σ_0) and the material strain at the proof stress (ε_0). For a plate in uniaxial longitudinal compression, the normalising expressions are:

$$\sigma' = \frac{\sigma_{xave}}{\sigma_0} \quad 8$$

$$\varepsilon' = \frac{\varepsilon_{xave}}{\varepsilon_0} \quad 9$$

All plates considered in this study have boundary conditions on all four sides which prevent out of plane displacement of the edges. A simply supported boundary condition is usually assumed to give a lower bound load shortening curve. The upper bound is usually the clamped plate.

Table 3 – Plate Boundary Conditions: 0 = Free, 1 = Constrained

	Simple Support		Clamped	
	AB and CD	BC and AD	AB and CD	BC and AD
Displacement x (u)	1 [*]	0	1 [*]	0
Displacement y (v)	0	1 [#]	0	1 [#]
Displacement z (w)	1	1	1	1
Rotation x (θ_x)	1	0	1	1
Rotation y (θ_y)	0	1	1	1
Rotation z (θ_z)	1	1	1	1

* AB is displacement controlled in X (longitudinal load), [#] BC constrained to move bodily in y but remain straight

Figure 8 – Plate coordinate system

All analyses are carried out using ABAQUS Standard and use the S4R standard element [2]. This was found to give comparable results compared to higher grade elements such as S8R. The standard mesh element length was determined through convergence analysis using several different plate configurations. Each element is set with 9 section integration points to ensure adequate through thickness stress calculation. For some of the 6082-T6 analyses the mesh size was further reduced to 10mm element length so as to adequately capture the localised plasticity near the plate boundary.

4.2. Imperfection Amplitude

The maximum imperfection, w_{0pl} , can be defined either from actual plate measurements or using a statistical representative value. Imperfection amplitude has a fundamental influence on the strength of a plate in compression. As imperfection amplitude is increased, the ultimate strength of the plate decreases. As an example, a set of load shortening curves for an otherwise identical plate with $\beta=2.0$ are shown in Figure 9, where imperfection amplitude is defined as:

$$w_{0pl} = C\beta^2 t$$

10

Results for a range of coefficients, C, between 0.05 and 0.55 are shown in Figure 9. Increased imperfection amplitude causes a lower initial stiffness prior to reaching the ultimate load together with lower peak strength. The shape of the peak and the post collapse relationship is somewhat flattened with increased amplitude. The relationship between imperfection amplitude and ultimate strength is demonstrated further in Figure 10 for plates of varying slenderness.

Figure 9 – Effect of imperfection amplitude – load shortening curves

Figure 10 – Effect of imperfection amplitude – ultimate strength curves

These results clearly demonstrate the need to explicitly define typical imperfection amplitudes in welded plate. A commonly used formulation is proposed by Smith et al. [16], who used extensive measurement data to determine slight, average and severe characteristic levels of imperfection typical of steel plate, corresponding to 3 percentile, mean and 97 percentile values of w_{0pl} .

$$w_{0pl} = \begin{cases} 0.025\beta^2 t & \text{(slight)} \\ 0.1\beta^2 t & \text{(average)} \\ 0.3\beta^2 t & \text{(severe)} \end{cases} \quad 11$$

The amplitudes calculated from the above formulae are representative only. The actual magnitude of deflection in a plate depends on many factors that are difficult to quantify numerically, including the quality of the fabrication process and how the plate has been treated in service.

Perhaps more important in the context of this study is that the above formulation is entirely based on measurements of steel plate. Equivalent formulae for aluminium alloy plate are not commonly found in open literature. One important source is the data collected during a ship structure committee project, which measured imperfections in 76 aluminium alloy stiffened panels. These were statistically analysed so as to formulate aluminium specific imperfection characteristics in the same form as Eq. 11. The resulting formulations are very similar to the equivalent steel plate equations and suggest that Eq. 11 is sufficient for direct use with aluminium. However, it must be noted that the measurements are based on plate manufactured by a single shipyard in a single batch and therefore may not constitute “typical” imperfections throughout the aluminium shipbuilding industry.

Figure 11 shows the influence of the three imperfection amplitudes as given in Eq. 11 for 5083-H116 and 6082-T6 plates. An assumption of severe imperfection causes a reduction in strength of up to 10% compared with the average whilst decreasing amplitude to slight causes an increase in strength of up to 4%. Variation in ultimate strength is greater in stocky plates.

Figure 11 – Effect of imperfection amplitude on 5083-H116 plates (left) and 6082-T6 plates (right)

4.3. Material Properties

Figure 12 compares the ultimate strength of the 2 aluminium alloys together with results for equivalent steel plate ($\sigma_0=245\text{MPa}$, $E=210\text{GPa}$, elastic perfectly plastic material representation). The 6082 plates show a significantly lower ultimate strength than the equivalent 5083-H116 plates. This is primarily due to the detrimental influence of the HAZ at the loaded edges of the plates, which is discussed in more detail in section 4.6.

Figure 12 – Comparison of the ultimate strength of 5083-H116, 6082-T6 and steel plates

4.4. Imperfection Shape

Imperfection shape has a significant effect on the load shortening curve relationship. For example, a previous study by Dow and Smith [32] took a detailed investigation of over 20 different imperfection shapes in unstiffened steel plate, demonstrating a significant variability in ultimate strength.

All imperfections modelled in this study use the conventional multiple mode Fourier series sine wave imperfection shape. To ensure a realistic and consistent idealisation of an actual plate with imperfection, a three mode imperfection series is used. The plate imperfection amplitude at a point of the plate surface, w , is described by the following equation:

$$\frac{w}{w_{0pl}} = \left(B_1 \sin \frac{\pi x}{a} + B_m \sin \frac{m \cdot x \cdot \pi}{a} + B_{m+1} \sin \frac{(m+1) \cdot x \cdot \pi}{a} \right) \sin \frac{\pi y}{b} \quad 12$$

where m is the lowest integer value such that:

$$m > \alpha \quad 13$$

where α is the plate aspect ratio:

$$\alpha = \frac{a}{b} \quad 14$$

Note that if the length is an exact multiple of the breadth (i.e. the aspect ratio is an integer) then m should be equal to the aspect ratio plus one. As an example, for a plate with aspect ratio 3, $m=4$. This ensures that the “square” wave imperfection lobes have a length shorter than the plate breadth.

The third term in the Fourier equation is included so that the plate imperfection is not symmetrical about the transverse centreline, thus ensuring buckling nucleates into one lobe of the plate only and prevents symmetrical buckling. An example of the influence of the third term is shown in Figure 13.

An otherwise identical plate is modelled with imperfection as given by Eq. 12; results are compared with the third coefficient $B_{m+1} = 0$ and $B_{m+1} = 0.01$. The NLFEM profile plots of the plate show the corresponding post collapse buckled shape (with x5 displacement magnification). The plots show a significant difference in the post collapse portion of the load shortening curve. This is because, with $B_{m+1} = 0$ (effectively reducing the imperfection to a two mode shape), the initial imperfection shape is symmetrical about the plate centreline. This means that the plate then buckles symmetrically, which in this particular case causes collapse to nucleate in both ends of the plate simultaneously. This has the effect of artificially increasing the displacement, thus “stretching” the strain axis on the corresponding load shortening plot. The inclusion of the third term in the Fourier series is clearly shown to prevent symmetrical buckling, with collapse nucleating into one end of the plate only.

Figure 13 – Comparison of mode shapes

The Fourier coefficients are given in Table 4 with adjustment to ensure the maximum amplitude (which is not necessarily at the centreline) is equal to w_{0pl} . The values of the coefficients B_1 , B_m and B_{m+1} are derived so as to give an 80%/20%/1% proportions of each Fourier term respectively.

Table 4 – Fourier coefficients

m	B_1	B_m	B_{m+1}
1	1	0	0
2	1.12	0.28	0.01
3	0.84	0.21	0.01
4	0.8	0.2	0.01
5	0.82	0.21	0.01
6	1.12	0.28	0.01
7 and above	0.8	0.2	0.01

4.5. Residual Stress

The influence of different residual stress patterns are compared in Figure 14. The stress patterns are:

- Longitudinal component only;
- Biaxial (longitudinal and transverse) components;
- Zero residual stress.

There are only very small differences between the three representations. The zero residual stress cases shows slightly higher ultimate strength than the other cases, particularly in the mid-range of the graphs between $\beta=2.0$ and $\beta=4.0$.

Figure 14 – Residual Strength 5083-H116 (left) 6082-T6 (right)

The influences of the HAZ in conjunction with the residual stresses are shown in Figure 15. As expected, the no HAZ models have higher ultimate strength than the equivalent plates with HAZ. The plot also shows that the residual stress has a more pronounced effect when there is no HAZ. The zero residual stress results are up to 5% higher than the equivalent plates with longitudinal residual stress.

Figure 15 – Residual Strength, 5083-H116 – comparison of models with and without HAZ

4.6. HAZ Location

The location of the HAZ depends on the build method for the panel. A standard approach in construction of orthogonally stiffened panels is to use large sheets of rolled plate, with stiffeners fillet welded at appropriate intervals. This is common when using 5xxx series plate, which is normally supplied as flat plate, with either 5xxx or 6xxx series stiffeners. Welding such a panel usually produces a HAZ pattern as shown in Figure 16a.

Alternatively a panel extrusion method is used, where the plate-stiffener section over one or more stiffener spaces is extruded in its entirety. Panels are then butt welded together, usually but not always at mid plate width. The extrusion is usually only one frame spacing in length, and transverse frames are therefore welded to the plate edges. The resulting HAZ pattern is sketched in Figure 16b. Equivalent HAZ distributions on the longitudinal edges only are shown in Figure 16c and Figure 16d.

A comparison of the effects of edge or centre HAZ location (a and b in Figure 16) is shown in Figure 17. Comparative load shortening curves for the different HAZ patterns are shown in Figure 18 (5083-H116) and Figure 19 (6082-T6).

The load shortening curves show that for these cases welded aluminium plates are weaker than equivalent un-welded plates but that the location of the longitudinal HAZ has a significant effect. The centre HAZ plates show increased stiffness compared to the edge HAZ plates prior to reaching the peak load. The peak strength is therefore higher. This phenomenon corresponds to the effective width concept whereby, as compressive load increases, the centre of the plate buckles and shirks loading, causing an increasing proportion of the load to be supported by the edge regions of the plate. Thus the strength of the longitudinal edges has a greater influence on the overall strength of the plate.

Figure 16 – Edge HAZ and Centre HAZ distributions

Figure 17 – Comparison of Ultimate Strength of Plates with different HAZ zones. 5083-H116 (left) and 6082-T6 (right)

Figure 18 - Comparison of HAZ location. 5083-H116 plates, $\beta=2.0$ (left), $\beta=3.0$ (right)

Figure 19 - Comparison of HAZ location. 6082-T6 plates, $\beta=2.0$ (left), $\beta=3.0$ (right)

The transverse HAZ, located on the short edges of the plate is caused by the weld joint connecting the plate to the transverse frames. The transverse HAZ can have a significant effect on the uniaxial strength and the collapse mode of the plate [13,27]. If the average compressive stress on the plate edge surpasses the reduced proof stress of the HAZ material, the end region can deform plastically and cause premature localised plate buckling.

Comparative tests on long 6082-T6 plates with varying slenderness show significant loss of compressive and tensile strength due to the presence of the transverse HAZ region. An example plot of the post collapse deformation shape for a plate with slenderness of 2.0 clearly shows localised failure in the end HAZ region (Figure 20). The softened proof stress ratio for 5083-H116 is less, and plates only show some effect at very low slenderness.

The effect of the transverse HAZ on the compressive ultimate strength is clearly shown in strength curves, presented in Figure 21. For slender plates the strength curve follows the same pattern as given by Faulkner's classic two term formula developed for steel plate [8]. With only longitudinal HAZ, both aluminium strength curves remain close to the Faulkner curve. However if the ultimate strength, given as a normalised stress ratio, is greater than the proof stress of the HAZ, the plate strength for cases with HAZ on all four edges is significantly affected, and the strength curve deviates away from Faulkner's line. The effect on 6082-T6 plate is much greater than for 5083-H116.

These findings have important implications when assessing the strength of welded aluminium structure, particularly if using 6xxx series alloy. If a weld line on a stocky plate is parallel to the loaded edge then that region may yield prior to buckling and result in a lower ultimate strength prediction for the plate.

Figure 20 – Example plots of the post collapse deformed shape (magnification x20) for a 6082-T6 plate with transverse HAZ (left) and without transverse HAZ (right).

Figure 21 - Comparison of transverse HAZ – 5083-H116 (left) and 6082-T6 (right) plates. Edge HAZ pattern.

4.7. HAZ Width

The extent of the HAZ is generally assumed to be a fixed distance (in this study $b_{HAZ} = 25\text{mm}$) regardless of the absolute dimensions of the plate. Thus the HAZ can be expected to have a more significant effect on a smaller plate where proportionally the softened area is larger.

A non-dimensional parameter to define the relative HAZ width on the longitudinal plate edges in relation to the total plate width is:

$$HR_L = \frac{2b_{HAZ,L}}{b}$$

15

Example load shortening curves comparing different HAZ ratios for 5083-H116 plates with $\beta = 2.0$ and $\beta = 3.0$ are shown in Figure 22. These demonstrate that HAZ width is a factor of influence for ultimate strength, with an increased HAZ lowering the ultimate capacity of the plate. HAZ width has less of an effect on the general shape of the load shortening curve.

Figure 22 – Comparison of HAZ width ratio

4.8. Aspect Ratio

It is generally assumed that the load shortening relationship is independent of aspect ratio for long plates. The assumption is verified by assessing the influence of plate aspect ratio, α using analyses of 60 plates with three widths (300,400 and 500mm) and aspect ratios between 0.2 and 5.0. All plates are specified with standard properties: 5083-H116 material, $\beta=2.0$, and with 25mm HAZ at all four edges. Plots of the ultimate strength - aspect ratio relationship are presented in Figure 23. The plots in Figure 23 show the same results at different scale and are intended to highlight different features of the aspect ratio relationship. The scatter plot demonstrates the overall correlation of all results whilst the line plot highlights the variation between results from plates with different width.

The plots show only slight variation in ultimate strength above aspect ratio of 1.5. The variation between results from plates with different width is due to the corresponding variation in the relative HAZ width, which has a significant effect on strength as discussed previously. The variation between strengths for plates of the same width is most likely due to the effect of imperfection shape on non-integer aspect ratios.

These results suggest that, in terms of ultimate strength analysis, the definition of a “long plate” is one with aspect ratio of at least 1.5. Below this value, the ultimate strength is highly dependent on

the aspect ratio. The plate strength reduces to a minimum at aspect ratio just less than unity (i.e. a square plate). At very small aspect ratios the ultimate strength is markedly increased. For aspect ratios less than unity the wide plate is effectively acting equivalent to a long plate under transverse compression.

Figure 23 – Influence of aspect ratio, 5083-H116 plates with $\beta = 2.0$.

4.9. Plate Load Shortening Curve Datasets

The previous sections have demonstrated the influence of several material and geometric parameters on the load shortening characteristics of aluminium plates. Of use in design are representative load shortening curves which describe a typical average plate. As an example, three load shortening curve datasets (5083-H116, 6082-T6 and 245MPa steel) are shown in Figure 24 to Figure 26. These are representative of typical plates and use the “base case” material and geometric properties as defined previously (section 4.1). The aluminium alloy results use a HAZ ratio of 0.125 with HAZ located at the four plate edges.

The sensitivity analyses have shown that dataset load shortening curves are significantly affected by the location and relative extent of the HAZ. Therefore, the load shortening datasets presented here are only valid for the specified HAZ ratio of 0.125.

Figure 24 – 5083-H116 plate load shortening curves with slight (top), average (centre) and severe (bottom) imperfections

Figure 25 – 6082-T6 plate load shortening curves with slight (top), average (centre) and severe (bottom) imperfections

Figure 26 – Steel plate load shortening curves with slight (top), average (centre) and severe (bottom) imperfections

5. Conclusions

The strength behaviour of aluminium plates under a progressively increasing longitudinal load is shown to be affected by a number of parameters including the aluminium alloy, geometric imperfection, HAZ distribution, level of softening and residual stress distribution. In particular, the HAZ distribution and relative size to the total plate breadth is shown to be a significant factor of influence in the load shortening behaviour. A HAZ ratio is therefore proposed, which must be accounted for when developing load shortening curve data for aluminium alloy plates.

The results show there is a moderate level of uncertainty in how to define a representative plate for numerical modelling. The study also shows that a rigorous definition of the plate imperfection characteristics is crucial when modelling a plate in isolation. This suggests that the same imperfection characteristics are also important when the plate forms part of a larger NLFEM model of a stiffened panel structure. The investigation of imperfection characteristics has been used to determine representative properties of a realistic plate. The approach used to model the geometric imperfections can be used to model a plate with arbitrary dimensions in NLFEM.

Using the representative plate modelling approach a parametric dataset of load shortening curves for aluminium plates under uniaxial longitudinal load have been derived. These can be adapted for use in a global assessment of the ultimate strength of an aluminium hull girder in a progressive collapse type analysis.

6. References

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