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Effect of welding on ultimate compressive strength of aluminium stiffened panels

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Abstract

Aluminium structures for marine applications have normally been built by welding. It is recognized that welding significantly affects the behaviour of aluminium alloys. In particular, heat-affected zone (HAZ) is softened by welding, and this reduces the ultimate strength of welded aluminium structures. It is of vital importance for structural designers to better understand how fabrication by welding affects the aluminium panel ultimate strength characteristics. This paper investigates the ultimate compressive strength characteristics of welded aluminium stiffened panels with varying welding related parameters such as weld type, width of HAZ (heat-affected zone) and reduction of yield stress due to HAZ softening, The non-linear finite element methods and the Paik empirical formulae are employed for the sensitivity analyses on the parameters.

1. Introduction

Both steel and aluminium structures for marine applications have usually been built by welding for the benefits in terms of fabrication efficiency and cost. However, welding can give rise to some problems during fabrication of aluminium structures in terms of softening in heat-affected zone (HAZ), among others, in contrast to low alloy steel structures. This may reduce the ultimate strength of welded aluminium structures.

It is commonly accepted that the collapse characteristics of welded aluminium structures are similar to those of welded steel structures until and after the ultimate strength is reached, regardless of the differences between them in terms of material properties. However, it is also recognized that the ultimate strength design formulae available for steel panels cannot be directly applied to aluminium panels even though the corresponding material properties are properly accounted for. One of the major reasons for this is due to the fact that the softening in HAZ significantly affects (reduces) the ultimate strength behaviour of welded aluminium structures, whereas it can normally be neglected in welded steel structures, Paik et al. (2004a).

A variety of parameters may affect the ultimate strength characteristics of welded aluminium structures as well as welded steel structures, and it is of vital importance for structural designers to better understand the sensitivity of the ultimate strength characteristics on such parameters. The aim of this paper is to provide one such contribution with the focus on the effect of welding on ultimate strength characteristics of welded aluminium panels, among other parameters. The parameters considered in the present paper are: weld type, HAZ width, and reduction of yield stress in the HAZ. The sensitivity on thickness of plating between stiffeners is also studied. With varying the parameters, a series of the ultimate strength calculations are undertaken. Non-linear finite element methods, Rigo et al. (2004), Simonsen (2003), and the empirical formulae of Paik et al. (2004a,b,c) are used for that purpose.

2. Methods of analysis

2.1 Non-linear finite element methods

Non-linear finite element solutions previously obtained by the ISSC Committee III.1 on Ultimate Strength, Simonsen et al. (2003), are adopted for the present sensitivity analyses. An elaborate description of the ISSC FEA is given by Simonsen et al. (2003) and Rigo et al. (2003). The FEA solutions previously obtained by Rigo et al. (2004) are also used for the present sensitivity analysis on weld locations.

2.2 The Paik empirical formulae

A first-cut estimate of the panel ultimate strength is very important in terms of ultimate limit state (ULS) based reliability analyses. In this case, an empirical formulae is often useful. Paik et al. (2004a,b) derived the ULS formulae for both welded aluminum plating (between stiffeners) and welded aluminum stiffened panels, by regression analyses of FE computations obtained with varying related parameters. Details of the FEA to develop the empirical formulae are given by Paik et al. (2004a,b).

Three different levels of initial deflections were considered for the FE computations (see section 3.6), while welding residual stresses were not considered. Therefore, the three different types of ultimate strength formulae for the three different levels of initial deflections were derived. The following is the Paik empirical formulae for aluminium stiffened panels with the symbols defined in Fig.1, Paik et al. (2004b,c):

$$\boxed{\sigma_{xu} = \frac{\sigma_{Y,seq}'}{\sqrt{C_1 + C_2(\lambda')^2 + C_3(\beta')^2 + C_4(\lambda'.\beta')^2 + C_5(\lambda')^4}} \le \frac{\sigma_{Y,seq}'}{(\lambda')^2}} \qquad (1)$$

σ_{xu} ultimate strength of the aluminium stiffened panel;

$\sigma_{Y,seq}'$ equivalent yield stress of plate-stiffener combination as representative of a stiffened panel with considering HAZ effect,

$$= \frac{P_S}{bt + h_w t_w + b_f t_f},$$

$$P_s = (b-2b_p')\, t\, \sigma_{Yp} + 2\, b_p'\, t\, \sigma_{Yp}' + (h_w - b_s')\, t_w\, \sigma_{Ys} + b_s'\, t_w\, \sigma_{Ys}' + b_f\, t_f\, \sigma_{Ys} \qquad (2)$$

b	breadth of plating;
b_f	breadth of stiffener flange;
b_p'	HAZ breath at plate;
b_s'	HAZ breadth at stiffener;
h_w	height of stiffener web;
t	thickness of plating;
t_f	thickness of stiffener flange;
t_w	thickness of stiffener web;
σ_{Yp}	yield stress of plating at 0,2% offset;
σ_{Yp}'	yield stress of plating in HAZ;
σ_{Ys}	yield stress of stiffener at 0,2% offset;
σ_{Ys}'	yield stress of stiffener in HAZ;
λ'	column slenderness ratio with considering the HAZ effect;

$$= \frac{a}{\pi r}\sqrt{\frac{\sigma_{Y,seq}'}{E}} \qquad (3)$$

a	length of a stiffened panel between transverse frames
E	Young's modulus of elasticity
r	radius of gyration,

$$r = \sqrt{\frac{I}{bt + A_w + A_f}};$$

I moment of inertia,

$$I=\frac{bt^3}{12}+bt\left(z_0-\frac{t}{2}\right)^2+\frac{h_w^3t_w}{12}+A_w\left(z_0-t-\frac{h_w}{2}\right)^2+\frac{b_ft_f^3}{12}+A_f\left(t+h_w+\frac{t_f}{2}-z_0\right)^2$$

$A_w = h_w t_w$;

$A_f = b_f t_f$;

z_0 distance from the outer surface of the attached plate to the elastic horizontal neutral axis of the plate-stiffener combination;

$$z_0=\frac{0.5bt^2+A_w(t+0.5h_w)+A_f(t+h_w+0.5t_f)}{bt+A_w+A_f}$$

β' plate slenderness ratio with considering the HAZ effect;

$$=\frac{b}{t}\sqrt{\frac{\sigma_{Y,p}'}{E}} \tag{4}$$

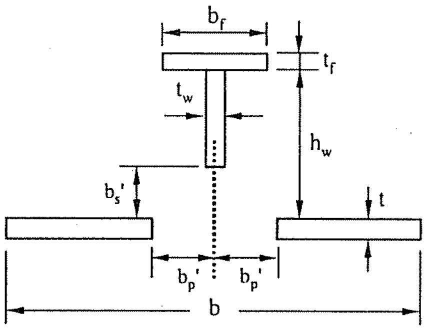


Fig.1: Cross section of the plate-stiffener combination with softening zones

In Eq.(1), the coefficients $C_1 - C_5$ are defined depending on the level of initial deflections of plating and stiffeners, as indicated in Table I, Paik et al. (2004b,c).

Table I: Coefficients depending on the levels of initial deflections of plating and stiffeners

Coefficient	Slight	Average	Severe
C_1	0.878	1.038	1.157
C_2	0.191	1.099	2.297
C_3	0.106	0.093	0.152
C_4	-0.017	-0.047	-0.138
C_5	1.30	1.648	3.684

3. Description of the standard panel considered

3.1 Geometry

For the present study, a reference panel is selected from welded aluminium stiffened panels used for collapse testing undertaken by Aalberg et al. (2001). The panel has angle type (or L-shaped) aluminum extrusions (6082 temper T6) of stiffeners, while the stiffeners are welded to plating. Fig.2 indicates the geometry of the reference panel.

3.2 Material properties

While the details of the material properties are described in the paper of Aalberg et al. (2001), the Young modulus is 70,475 MPa and the Poisson ratio is 0.3. The transverse frames have the same material properties to plating. Welding significantly influences the properties of aluminium alloys.

Due to welding, the yield stress in HAZ can be decreased. Depending on the weld type, the width of HAZ can increase. In this regard, the HAZ width and the reduction amount of yield stress in HAZ will be varied in the present sensitivity analyses.

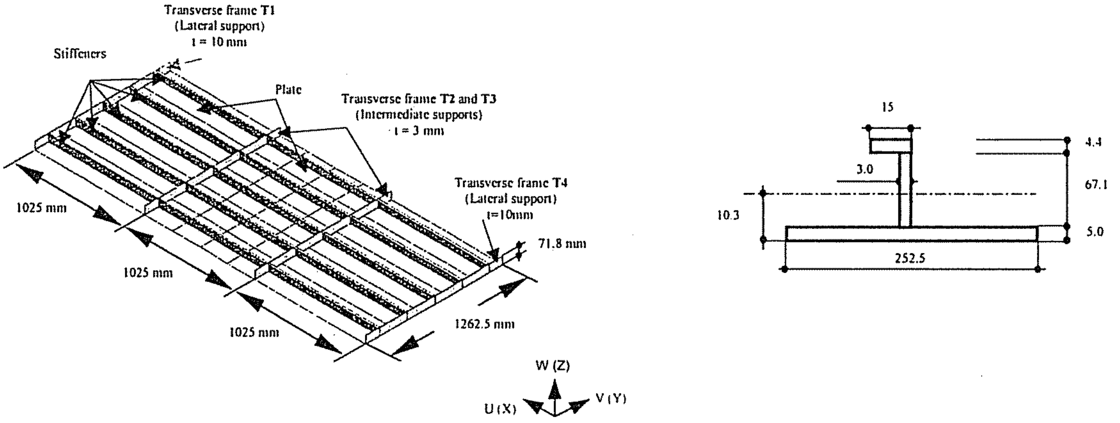


Fig.2: The reference aluminium stiffened panel

3.3 Loads

The panel is subjected to axial compressive loads in the longitudinal direction applying displacement control. Loading is applied at the initial neutral axis of cross section at both ends (no shift due to eccentric load, etc. is considered).

3.4 Extent of the analysis

In the ISSC FEA, the entire panel, i.e., with a three-bay was taken as the extent of the analysis. The Rigo FEA takes a two-bay model, i.e., 1/2+1+1/2 panels as shown in Fig.3. On the other hand, a plate-stiffener combination model, i.e., a single stiffener with associated plating between transverse frames was taken for the Paik et al. (2004a) FEA which produced the Paik empirical formulae.

3.5 Boundary conditions

In the ISSC FEA, all (four) edges of the panel are almost clamped, while both the Rigo FEA and the Paik FEA consider that the panel is simply supported.

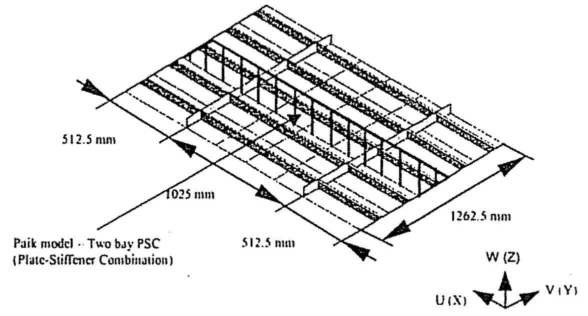


Fig.3: Extent of the analysis used for the Rigo FEA

3.6 Initial imperfections

In the ISSC FEA, a unique type of initial deflection is artificially generated as shown in Fig.4. A uniform lateral pressure loading is applied until the maximum deflection of plating between stiffeners is 2mm.

It is important to realize that the resulting initial deflection pattern generated by the ISSC FEA is quite different from the collapse mode of the continuous stiffened panel under predominantly axial compressive loads. That is, all sub-panels in this situation deflect in the same direction, although one sub-panel buckles up while the adjacent sub-panels deflect down as long as axial compressive loads are predominant. As a result, this unique pattern of initial deflection considered in the ISSC FEA can increase the panel ultimate strength to some extent.

Also, the ISSC FEA does not properly consider the initial deflection of stiffeners in the direction parallel or normal to stiffener web, the former being called column type initial deflection of stiffener and the latter being called sideways initial deflection of stiffeners.

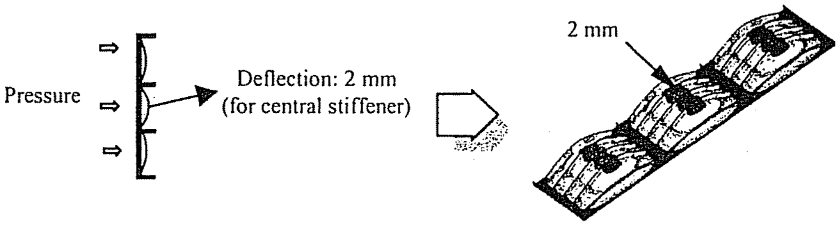


Fig. 4: Generation of initial deflection - Procedure to define the initial imperfections adopted for the ISSC FEA

The Rigo FEA considers two types of initial deflection pattern: One is the same to that of the ISSC FEA noted above, and the other is that the initial deflection pattern of plating between stiffeners is the same to the original buckling half wave.

While the Paik FEA assumes that plating between stiffeners has the same pattern to the original buckling half wave, it considers the three types of initial deflections, namely the initial deflection of plating between stiffeners, the column type initial deflection of stiffeners and the sideways initial deflection of stiffeners. Also, three different levels of initial deflections were considered in the Paik FEA, as follows

Slight level : $w_{opl} = 0.003b$, $w_{oc} = w_{os} = 0.001a$
Average level : $w_{opl} = 0.009b$, $w_{oc} = w_{os} = 0.0025a$
Severe level : $w_{opl} = 0.015b$, $w_{oc} = 0.005a$, $w_{os} = 0.008a$

where w_{opl} = maximum initial deflection of plating between stiffeners, w_{oc} = maximum column type initial deflection of stiffeners in the direction parallel to stiffener web, w_{os} = maximum sideways initial deflection of stiffeners in the direction normal to stiffener web, b = breadth of plating between stiffeners, and a = length of a stiffened panel between transverse frames.

Welding induced residual stresses are not considered for both the ISSC and Paik finite element analyses.

3.7 Modelling of HAZ

According to several standards, one shall consider the width of the reduced strength zone (noted η_1 and η_2 in the following) to extend 25 mm at each side of the weld (note that 20 mm is proposed in Eurocode 9, ENV (1998). In the present study (Fig.6), this indicates that $2\,\eta_1 = 50$ mm in the plate and $\eta_2 = 25$ mm in the stiffener web (measured from the mid-plate and not from the plate surface). The extension (width) of the HAZ is mainly affected by the applied welding process and the welding parameters, as well as the material properties.

Therefore, the following weld zones are considered in the mesh modelling (Fig. 6):

- five longitudinal welds at the junction between the transverse plate and the five stiffeners,
- four longitudinal welds at the intersection between the five extruded elements,
- two transverse welds between plates.

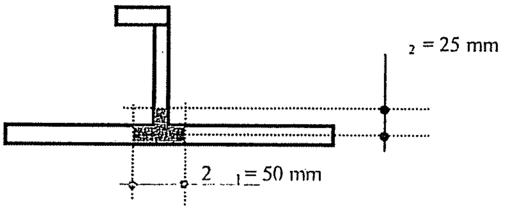


Fig. 5: Standard HAZ width (2 η_1 in plate = 50 mm, η_2 in stiffener web = 25 mm)

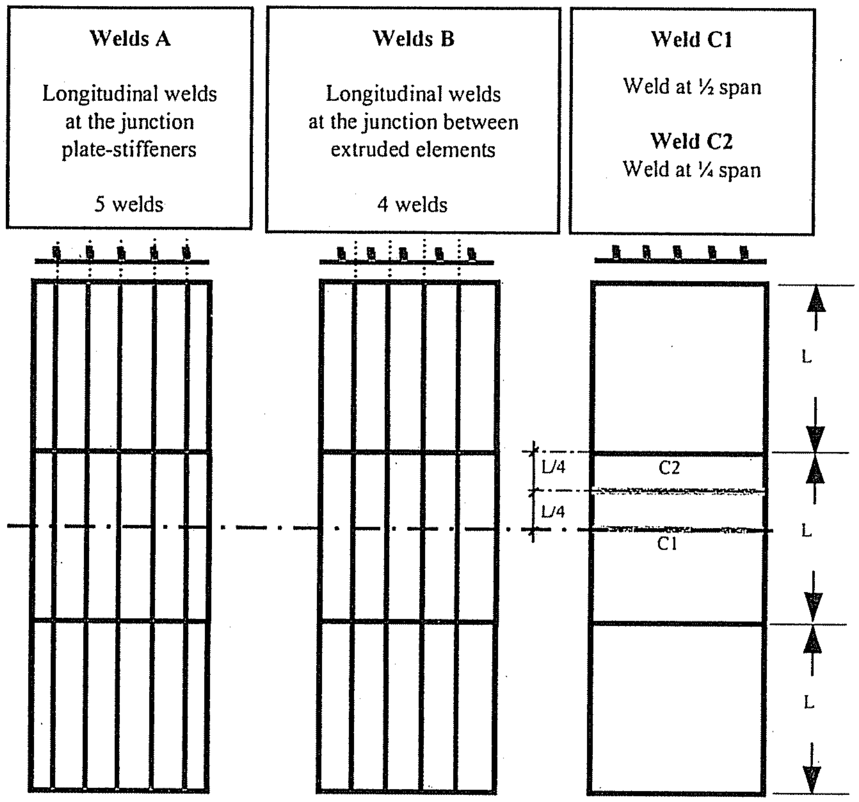


Fig. 6: Weld positions considered

It is assumed that welding does not affect material in HAZ of the transverse frames (i.e., T1,...,T4). Unless otherwise specified, the FEA is conducted with the HAZ width of 50 mm, i.e. 2 η_1 =50 mm (2×25 mm in the plate) and η_2=25 mm in the stiffener flange, with η_1 and η_2 defined in Fig. 5.

4. Sensitivity analysis

4.1 Weld locations

The ISSC FEA, Simonsen et al. (2003):

Table II: Effect of the weld locations investigated by the ISSC FEA

	Without HAZ (reference)	Welds A	Welds B	Welds B+C1	Welds A+C1	Welds A+C2	Welds B+C2
Ultimate strength (N/mm²)	167.5	140.3	159.6	144.1	126.0	133.7	142.1
Difference to reference (%)	Ref.	-16.2	-4.7	-14.0	-24.8	-20.2	-15.2

Rigo et al. (2004) FEA:

Table III: Effect of the weld locations investigated by the Rigo FEA with the initial deflection pattern of the ISSC FEA

	Without HAZ (reference)	Welds A	Welds B	Welds B+C1	Welds A+C1	Welds A+C2
Ultimate strength (N/mm²)	159.6	146.8	151.0	141.7	130.6	128.3
Difference to reference (%)	Ref.	-8.0	-5.4	-11.2	-18.2	-19.6

Table IV: Effect of the weld locations investigated by the Rigo FEA with the initial deflection pattern of the buckling half wave

	Without HAZ (reference)	Welds A	Welds B	Welds B+C1	Welds A+C1	Welds A+C2
Ultimate strength (N/mm²)	141.2	127.9	139.6	139.8	128.4	128.5
Difference to reference (%)	Ref.	-9.4	-1.1	-1.0	-9.1	-8.9

Paik et al. (2004a,b,c) empirical formulae:

Table V: Effect of the weld locations investigated by the Paik empirical formulae for an average level of initial deflection

	Without HAZ (reference)	Welds A	Welds B
Ultimate strength (N/mm²)	125.1	117.8	119.5
Difference to reference (%)	Ref.	-5.8	-4.5

It tends that the reduction of the ultimate strength due to weld type A is more serious than that due to weld type B. Compared to those by the ISSC FEA or the Rigo FEA, the reduction amount of the ultimate strength for welds B (extruded element) is similar to that for welds A (stiffeners welded on the plate) when the Paik empirical formulae are used. This may be due to the fact that in using the Paik empirical formulae, welds B are only taken into account through the P_s expression (Eq.(2)) which becomes:

$$P_s = (b-2b_p') \, t \, \sigma_{Yp} + 2 \, b_p' \, \sigma_{Yp}' + h_w \, t_w \, \sigma_{Ys} + b_f \, t_f \, \sigma_{Ys} \tag{5}$$

Transverse weld location seems insignificant but cannot be neglected as a difference is recorded between weld C1 and weld C2. Note that the Paik formulae does not consider the effect of welding along transverse frames as well since the plate-stiffener combination model is employed for the ULS calculation of a stiffened panel.

4.2. Effect of HAZ width (with Welds A – welded Stiffeners)

Four HAZ widths ($2\,\eta_1$ in plate and η_2 in web) are considered (Fig. 5): $2\,\eta_1 = 25, 50, 75, 100$ mm ($\eta_1 = \eta_2$). The yield stress in the HAZ is fixed at 115 MPa.

The ISSC FEA, Simonsen et al. (2003):

Table VI: Effect of the HAZ width investigated by the ISSC FEA

	Without HAZ (reference)	HAZ width			
		25 mm	50 mm	75 mm	100 mm
Ultimate strength (N/mm²)	167.5	157.2	149.8	142.3	137.0
Differenece to reference (%)	Ref.	-6.1	-10.6	-15.0	-18.2

Paik et al. (2004a,b,c) empirical formulae:

Table VII: Effect of the HAZ width investigated by the Paik empirical formulae

Initial deflection level		Without HAZ (reference)	HAZ width (mm)			
			25mm	50mm	75mm	100mm
Slight level	Ultimate strength (N/mm²)	143.7	135.3	125.4	113.8	100.1
	Difference to reference	Ref.	-5.9	-12.7	-20.8	-30.4
Average level	Ultimate strength (N/mm²)	125.1	117.6	108.9	98.9	87.1
	Difference to reference	Ref.	-6.0	-13.0	-21.0	-30.4
Severe level	Ultimate strength (N/mm²)	95.3	90.3	84.5	77.7	69.6
	Difference to reference	Ref.	-5.2	-11.3	-18.5	-27.0

Fig.7 shows the effect of the HAZ width on the panel ultimate compressive strength when weld type A is applied. The panel ultimate compressive strength decreases significantly as the HAZ width increases. The reduction tendency of the ultimate strength with increase in the HAZ width is similar for both the ISSC FEA and the Paik empirical formulae regardless of the differences in terms of the panel edge conditions and the magnitude of initial deflections considered. The panel ultimate compressive strength is also affected significantly by the initial deflections.

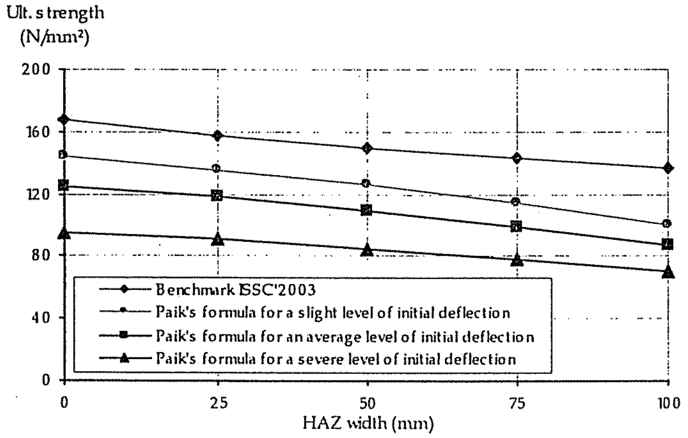


Fig.7: Sensitivity on HAZ width

4.3. Effect of yield stress reduction in the HAZ

The yield stress in the HAZ is varied when the HAZ width is fixed at 2 η_1 = 50 mm.

The ISSC FEA, Simonsen et al. (2003):

Table VIII: Effect of the yield stress reduction in the HAZ investigated by the ISSC FEA

	Without HAZ (reference)	Yield stress (N/mm²)					
		$S_{Y,ref}$ − 10	$S_{Y,ref}$	$S_{Y,ref}$ + 10	$S_{Y,ref}$ + 20	$S_{Y,ref}$ + 40	$S_{Y,ref}$ + 60
Ultimate strength (N/mm²)	167.5	148.4	150.3	152.4	154.4	160.0	167.7
Difference to reference (%)	Ref.	-1.3	0.0	1.4	2.7	6.4	11.6

Paik et al. (2004a,b,c) empirical formulae:

Table IX: Effect of the yield stress reduction in the HAZ investigated by the Paik empirical formulae

Initial deflection level		Without HAZ (reference)	Yield stress (N/mm^2)					
			$S_{y,ref}-10$	$S_{y,ref}$	$S_{y,ref}+10$	$S_{y,ref}+20$	$S_{y,ref}+40$	$S_{y,ref}+60$
Slight level	Ultimate strength (N/mm^2)	143.7	134.6	135.3	135.9	136.5	137.7	138.9
	Difference to reference	Ref.	-7.2	-6.7	-6.2	-5.7	-4.8	-3.8
Average level	Ultimate strength (N/mm^2)	125.1	117.0	117.6	118.1	118.7	119.8	120.8
	Difference to reference	Ref.	-6.5	-6.0	-5.6	-5.2	-4.3	-3.4
Severe level	Ultimate strength (N/mm^2)	95.3	89.9	90.3	90.7	91.0	91.8	92.5
	Difference to reference	Ref.	-5.9	-5.5	-5.1	-4.7	-3.6	-3.1

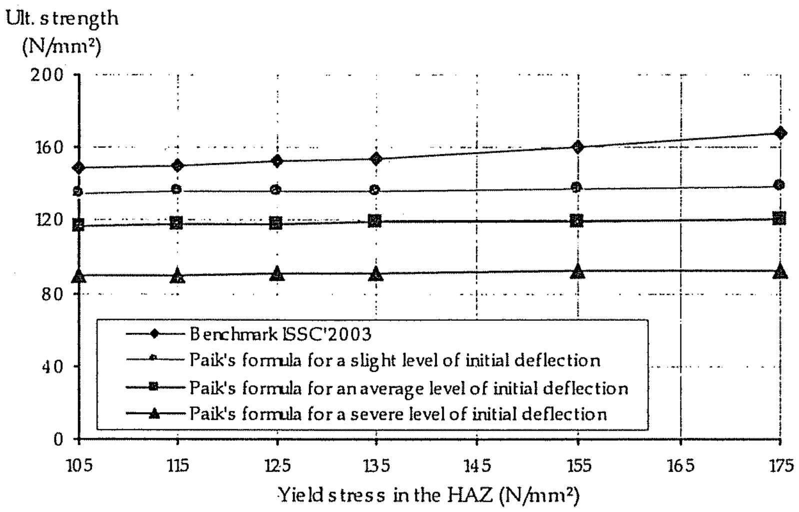


Fig.8: Sensitivity on yield stress of the HAZ

Fig.8 shows the effect of yield stress in HAZ on the panel ultimate compressive strength. The Paik empirical formulae indicates that the sensitivity of the panel ultimate strength on the yield stress in the HAZ is very small, while a reduction of 10% yield stress in the HAZ results in an ultimate strength reduction varying from 2% to 5% in the ISSC FEA. While further study is pending, this might be due to the fact that the tensile residual stresses exist in the HAZ after welding and this should usually not affect the ultimate strength of the panel as long as compressive loads are applied and the HAZ width is relatively small.

4.4. Effect of plate thickness

The thickness of the plate between stiffeners was increased to 7 mm, keeping the rest of the geometry of stiffeners unchanged. The material properties correspond to welds A, where the width of the HAZ is 2 η_1 = 50 mm.

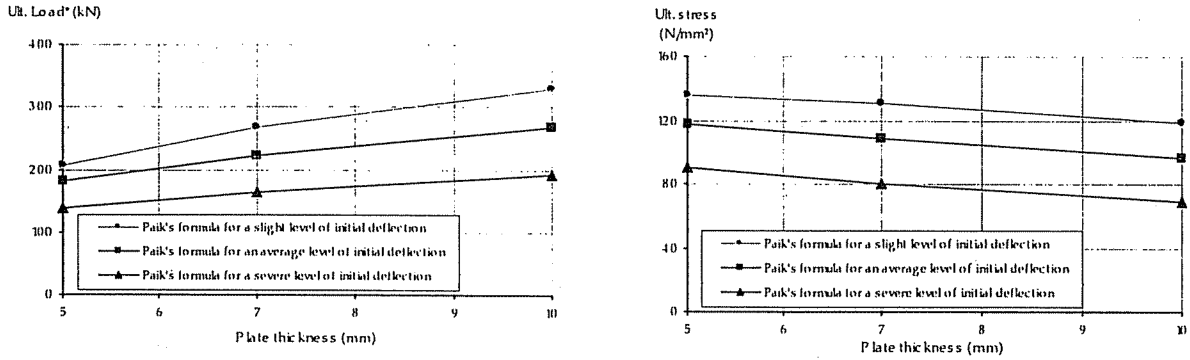
Paik et al. (2004a,b,c) empirical formulae:

Table X.a: Effect of plate thickness on the ultimate load investigated by the Paik empirical formulae

Initial deflection level		Plate thickness (mm)		
		5mm	7mm	10mm
Slight level	Ultimate load (kN)	206.9	266.8	329.9
	Difference to reference	Ref.	28.9	12.7
Average level	Ultimate load (kN)	179.9	221.1	267.8
	Difference to reference	Ref.	22.9	48.9
Severe level	Ultimate load (kN)	137.9	162.7	191.4
	Difference to reference	Ref.	18.0	38.8

Table X.b: Effect of plate thickness on the ultimate stress investigated by the Paik empirical formulae

Initial deflection level		Plate thickness (mm)		
		5mm	7mm	10mm
Slight level	Ultimate strength (N/mm^2)	135.3	131.1	118.1
	Difference to reference	Ref.	-3.1	-12.7
Average level	Ultimate strength (N/mm^2)	117.6	108.6	95.9
	Difference to reference	Ref.	-7.6	-18.4
Severe level	Ultimate strength (N/mm^2)	90.1	79.9	68.5
	Difference to reference	Ref.	-11.3	-24.0



*Ultimate load = resultant of the ultimate stress on the section of the plate-stiffener combination (Fig.2)

Fig 9: Sensitivity on plate thickness

Fig.9 shows the effect of plate thickness on the ultimate load and the ultimate stress of the panel, respectively. As would be expected, the ultimate load (force) increases with increase in the thickness of plating between stiffeners. However, the ultimate stress decreases as the thickness of plating increases while the dimensions of stiffeners are kept unchanged. This is due to the fact that for this specific case, the panel collapses by lateral-torsional buckling (or tripping) when the thickness of plating was increased to 7mm, while the standard panel reached the ultimate limit state by the so-called beam-column type collapse mode.

This is because stiffeners are likely to fail prior to plating as stiffeners are comparatively weak than plating with increased thickness, while the panel cross sectional area increases. It may be surmised from this study that a careful design of panel structures is required considering the potential collapse modes to occur as well as scantlings themselves.

5. Conclusions

In this paper, the effects of welding related parameters on the ultimate compressive strength of aluminium stiffened panels are investigated. The following conclusions can be drawn:

1. Welding related parameters studied in the present study are weld locations, HAZ width and yield stress reduction in HAZ. In addition, the effect of plate thickness on the panel ultimate strength is also studied.
2. It is concluded that fillet-welding at the junction between plating and stiffeners is more likely reducing the panel ultimate compressive strength than that by butt-welding of I-shaped extrusions. This is because the stiffener web as well as plate part is also softened in the former type of welding, while only plate part is softened in the latter.
3. As the width of HAZ increases keeping the yield stress in HAZ constant, the panel ultimate compressive strength decreases significantly.
4. As long as the HAZ width is relatively small and compressive loads are applied, the effect of yield stress reduction in the HAZ is small. This is because the tensile residual stresses existed in HAZ may offset the reduction of the ultimate strength of the panel in axial compression, while further study is pending when the HAZ width becomes larger.
5. When the dimensions of stiffeners are kept unchanged, the panel ultimate compressive strength (stress) can rather decrease with increase only in the thickness of plating between stiffeners. This is due to the fact that the collapse mode of the panel can become changed from the beam-column type collapse to lateral-torsional buckling of stiffeners as the stiffeners become weak compared to plating between stiffeners so that stiffeners likely fail prior to plating between stiffeners.

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