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# Ultimate strength of aluminium stiffened panels: Sensitivity analysis

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## Abstract

The "Ultimate Strength" committee of ISSC'2003 carried out a benchmark on the ultimate strength of aluminium stiffened panels. The purpose of this benchmark was, for a given aluminium stiffened panel, to quantify the variations of the panel's ultimate strength when panel's parameters change. The studied parameters are weld types, HAZ width, yield stress in the HAZ, initial panel deflection and residual stresses.
In this paper the authors focus their discussion on the main outcomes provided by the ISSC benchmark and present additional analysis performed to confirm the previous results. Finally the authors propose recommendations for future research works.

## Author keywords

Ultimate strength; Sensitivity analysis; Aluminium stiffened panels; Axial compression; Heat-affected zone

## Introduction

In San Diego (August 2003) the "Ultimate Strength" committee of ISSC'2003 presented a brief report about their benchmark on the ultimate strength of aluminium stiffened panels [Simonsen et al., 2003]. For additional information on the benchmark itself, a comprehensive paper in Marine Structures [Rigo et al., 2003] is now available. The present paper provides additional and updated results that are not available in the previous documents

The authors of this paper are the researchers that performed the ISSC benchmark. They thank all the ISSC'2003 III.1 committee and particularly S. Estefen, E. Lehman and B.C. Simonsen (committee chairman) for their support and advices.

The purpose of the ISSC benchmark was, for a given aluminium stiffened panel, to quantify the variations of the panel's ultimate strength when panel's parameters change. These variations are called the sensitivities of the panel. The studied parameters are:

- Weld types (longitudinal, transversal, extruded and no extruded components),
- HAZ width,
- Yield stress in the HAZ,
- Initial panel deflection (amplitude and shape),
- Residual stresses.

The previous results presented in [Rigo et al., 2003 and Simonsen et al., 2003] based on a three-spans model are compared to new analysis performed with a ½ +1+ ½ model and with other initial deflection pattern (as recommended by the official discusser of ISSC-III.1 Committee in San Diego, 2003)

The data used in this analysis are taken from Aalberg experiments [Aalberg et al., 2001].

## Reference panel description

### *Geometry*

A panel with L-shaped stiffeners fabricated from extruded aluminium profiles in alloy AA6082 temper T6, joined by welding, was defined for the finite element analyses.
In the ISSC benchmark a three-spans model was considered while additional analyses were performed with a standard ½ + 1 + ½ model. The dimensions of the models are presented in Fig.1 with the XYZ coordinate frame and the U, V, W corresponding displacements.

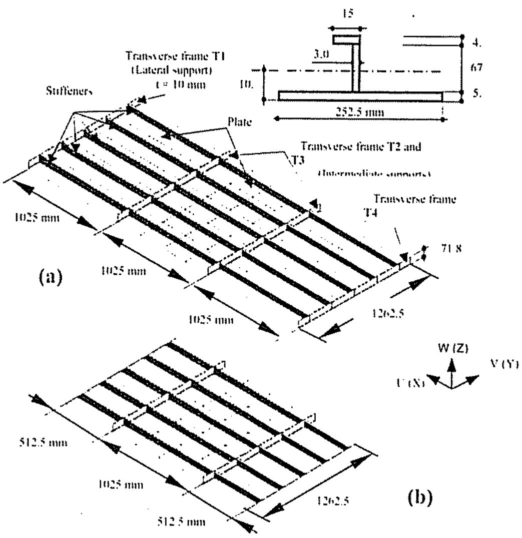

**Fig.1:**
**(a) ISSC three-spans model**
**(b) Standard ½ + 1 + ½ model**

### *Loads*

Only axial compressive loads are applied at the initial neutral axis at both ends (no shift due to eccentric load, etc. is assumed). Deadweight is not considered and a uniform temperature is assumed.

### *Material properties*

The material is assumed isotropic with a Poisson's ratio of 0.3 and a Young Modulus of 70,475 N/mm$^2$. The material properties were taken from the Aalberg experiments [Aalberg et al., 2001]. The same material properties are considered for the transverse frames.

The aluminium material strength in the HAZ is reduced by the high temperature during weld thermal cycle (MIG welded).

True stresses versus true strain properties derived from engineering values were implemented by each user into his FE model for plate, stiffeners and HAZ.

### *Boundary conditions*

In the present FE computations, the boundary conditions for the stiffened panels were assumed simply supported along the two longitudinal edges (unloaded), which are kept straight (constrained edges). The loaded edges were restrained from rotation and an axial displacement was prescribed on one side (clamping conditions for the ISSC model and symmetric conditions for the Standard model – the Standard model is then less stiff). At these two loaded edges, the stiffener cross-section remains plane and the sideways deformation of the stiffeners are not allowed. In order to simulate stiff transverse frames, the displacements ($W$) along $Z$ at the location of these transverse plates are not allowed.

### *Initial imperfections*

In the ISSC benchmark plate and stiffener imperfections were considered using the following procedure (Fig. 2): a uniform lateral pressure is applied (on the opposite side of the stiffener—tip of stiffener in tension) on the overall structure. The pressure has to remain small to stay in the elastic range. The pressure was calibrated to obtain a linear elastic deflection ($W$) of 2 mm at the central point of the central panel, i.e. at mid-span of the central stiffener. Shape and amplitude of the initial imperfections (for plates and stiffeners) are assumed identical to the deflections induced by the uniform lateral pressure. The considered initial deflection shape is of a thin-horse mode and is composed of several deflection components including the local buckling mode.

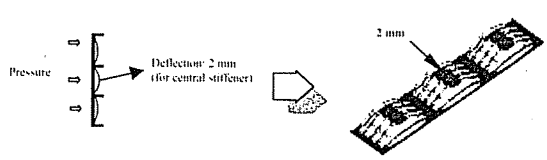

**Fig. 2: ISSC procedure to define the initial imperfections**

Additional analyses were performed with the Standard model using as initial imperfections the first buckling mode (m = 4) from eigenvalue buckling analysis scaled so that the maximum deformation remains 2 mm (Standard procedure).

### *HAZ modelling*

According to several standards, one shall consider the width of the reduced strength zone (noted $\eta_1$ and $\eta_2$ in the following) to extend 25 mm at each side of the weld (note that 20 mm is proposed in Eurocode 9 [Eurocode 9, 1998]). In the present study (Fig. 3), this means 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.

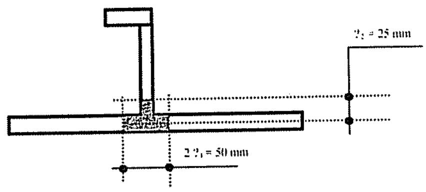

**Fig. 3: Standard HAZ width (2 $\eta_1$ in plate = 50 mm, $\eta_2$ in stiffener web = 25 mm)**

Therefore, the following weld zones were considered in the mesh model (Fig. 4):

- 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.

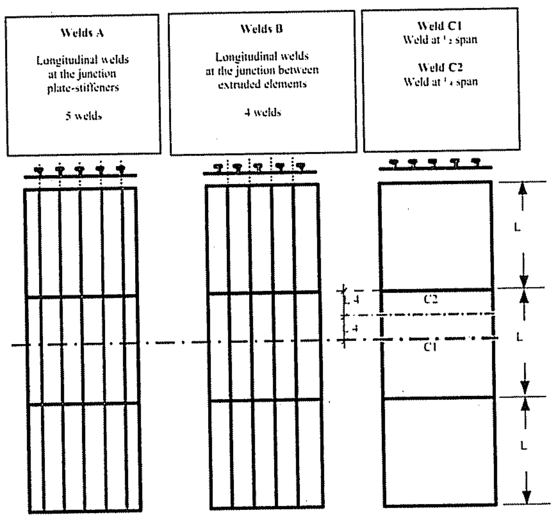


**Fig. 4: Weld positions**

It was assumed that the HAZ does not affect the transverse frames material (T1,...,T4).

If not specified, the numerical analyses were conducted with a HAZ width of 50 mm, i.e. 2 $\eta_1$ = 50 mm (2×25 mm in the plate) and $\eta_2$ = 25 mm in the stiffener flange, with $\eta_1$ and $\eta_2$ defined in Fig. 3.

## Finite element analyses

Two phases were planned. The aim of *Phase A* was intended as a calibration assessment. At the end of this phase, the participants were confident about the quality of their FE models. *Phase A* is not discussed in this report.

Then, for *Phase B*, the participants selected a series of parameters for the sensitivity analyses and each contributor performed different analysis. These parameters are:

- Weld types (longitudinal, transversal, extruded and no extruded components). Several configurations are studied–*Phase B*1,
- HAZ width (2 $\eta_1$ =25–100 mm)–*Phase B*2,
- Initial panel deflection (amplitude and shape)–*Phase B*3,
- Residual stresses—*Phase B*4,
- Yield stress in the HAZ—*Phase B*5.

### *Phase B1–weld types*

The influence of weld types was studied in this phase. Fig.5, Fig.6 and Table 1 show the results of the analyses that are compared to the reference case (without HAZ).

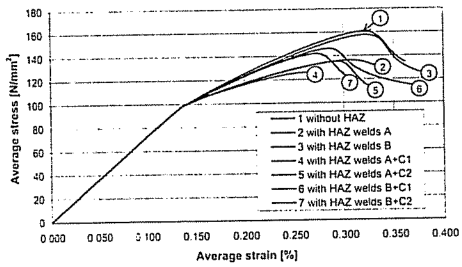


**Fig.5: Effect of the HAZ (ISSC model and ISSC initial imperfections)**

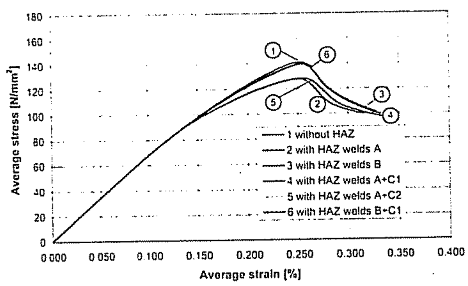


**Fig.6: Effect of the HAZ (Standard model and Standard initial imperfections)**

**Table 1: Effect of the HAZ – Reduction of maximum average stress to reference (without HAZ)**

| Weld types | Reduction [%] | | |
|---|---|---|---|
| | A* | B | C |
| Welds A | 13.4 –21.5 | 8.0 | 9.4 |
| Welds B | 1.3 – 9.1 | 5.4 | 1.1 |
| Welds A + C1 | 25.6 – 27.5 | 18.2 | 9.1 |
| Welds A + C2 | 22.1 – 23.4 | 19.6 | 8.9 |
| Welds B + C1 | 12.6 – 18.2 | 11.2 | 1.0 |
| Welds B + C2 | 18.1 | not considered | |
| Without HAZ [N/mm²] | 160.8 – 173.5 | 159.6 | 141.2 |

with A ISSC model and ISSC initial imperfections
B Standard model and ISSC initial imperfections
C Standard model and Standard initial imperfections

* *Interval of values obtained during the ISSC benchmark using different software and meshing features*

*Phase B2–HAZ width (with Welds A–welded stiffeners)*

In *Phase B2*, the sensitivity analysis concerns the HAZ width (simulations with Welds A). Four HAZ widths (2 $\eta_1$ in plate and $\eta_2$ in web) were considered (Fig. 3): 2 $\eta_1$ = 25, 50, 75, 100 mm ($\eta_1 = \eta_2$). Fig. 7 and Fig. 8 show the results of these analyses, which are compared to the reference case (without HAZ).

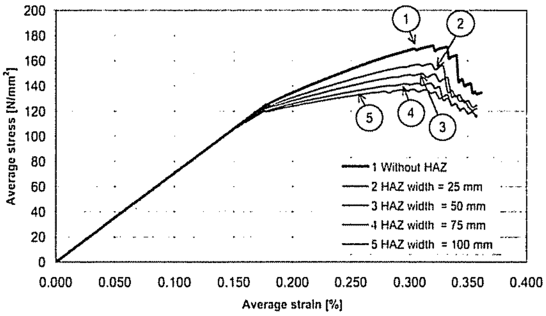


**Fig. 7: Sensitivity on the HAZ width (2 $\eta_1$ =25–100 mm) (ISSC model and ISSC initial imperfections)**

The variation of ultimate strength is not proportional to the HAZ width (2 $\eta_1$). The first 25 mm of the HAZ width are the most significant and have the larger effect on the ultimate strength.

For the considered model with Welds A, we observed (Fig. 8):

- for 2 $\eta_1$ = 25 mm, the reduction is approximately 9%,
- for 2 $\eta_1$ = 50 and 75 mm, the additional reduction of ultimate strength is about 4.5%,
- for 2 $\eta_1$ = 100 mm, the additional reduction of ultimate strength becomes smaller, approximately 3.0%.

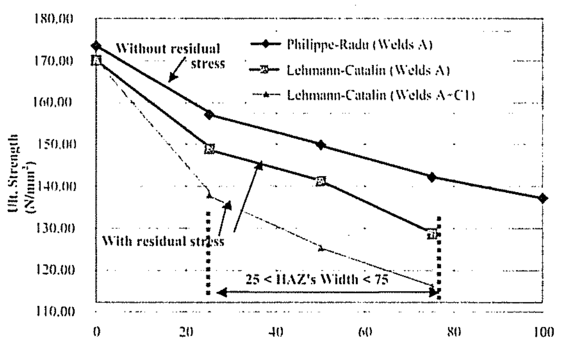


**Fig. 8: Sensitivity on the HAZ width (Welds A and A+C1, 2$\eta_1$ =25–100 mm) (ISSC model and ISSC initial imperfections)**

*Phase B3–initial imperfection*

The influence of the amplitude and shape of initial imperfection was studied in this phase (without HAZ). The amplitude is considered at the reference point, which is in the centre of the panel. This deflection may be different from the panel's maximum deflection, as significant local plate deflection may occur.

*Shape effect (sensitivity assessment):* Two shapes of initial deflection on the standard ½ + 1 + ½ model were considered in the analyses: the initial imperfections defined by the ISSC procedure (uniform lateral pressure) and those defined by the Standard procedure (first buckling mode).

Even if the two shapes differ, the corresponding stress–strain curves are quite similar (Fig. 9).

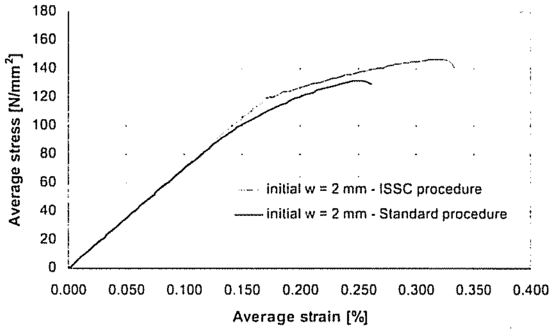


**Fig. 9: Influence of the initial imperfections shape (Standard model with Welds A)**

The deflection produced in the panel by lateral pressure is different from the local buckling mode (Standard procedure). This deflection is of a thin-horse mode and is composed of many deflection components including the local buckling mode. If only the buckling mode is given as initial deflection, buckling mode gradually develops when the load approaches the buckling load. However, when a thin-horse mode is assumed as initial deflection, other components restrain the development of the buckling mode until the load exceeds the buckling load. As a result, very clear buckling behaviour is observed as indicated in Fig. 10. This buckling behaviour could be accompanied by a snap-through if the load at which buckling deflection appears is higher than the buckling load in simply supported mode. Fig. 10 gives the deflection history of the centre point of two adjacent plates. Due to the initial deflection shape, the deflections at the two points are initially identical. Latter, for higher compressive load, the two plates buckle but in opposite direction. As the initial deflection shape differs completely from the shape of the collapse mode, it induces a strengthening of the structure.

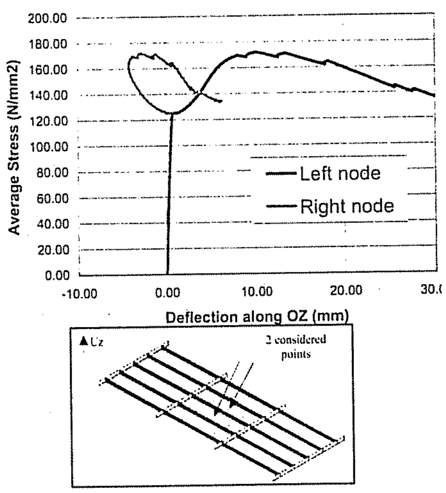


**Fig. 10: Shape of the plate collapse mode (ISSC model without HAZ). Stress–deflection curves at the centre of two consecutive plates.**

*Amplitude effect (sensitivity assessment):* Sensitivity assessment is obtained from Fig. 11. On average, for the ISSC model, each millimetre of initial deflection induces about 1.1% of reduction of the ultimate strength. Such a small variation shows that the amplitude of the initial deflection is not a key factor (for the considered panel).

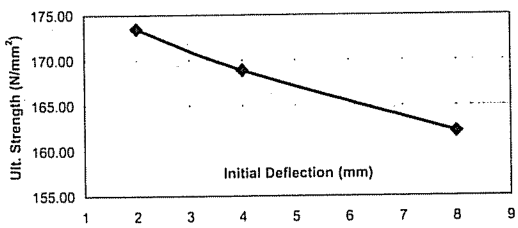


**Fig. 11: Effect of the amplitude of the initial deflection (ISSC model and ISSC initial imperfections)**

### *Phase B4—residual stresses*

In this phase, the effect of the residual stresses in the HAZ on the ultimate strength of the panel was analysed. Checking the effect of welding is, of course, a very difficult task. The simulation of welding itself is beyond the scope of work of the ISSC committee. However, a simplified distribution of residual stresses was assumed (Fig. 12) which was implemented in the FE model as initial stresses.

It is assumed that the initial tensile stresses extend over the entire HAZ width and are uniform over the width (2 $\eta_1$) and through the plate thickness. Their direction is parallel to the welding seam and the magnitude is equal to the flow limit of the material of the HAZ, i.e. 130 N/mm². This is valid for the stresses in the plate, as well as for the stresses in the stiffener. If not specified, the standard HAZ width (2 $\eta_1$) is 50 mm in the plate and 25 mm into the webs ($\eta_2$).

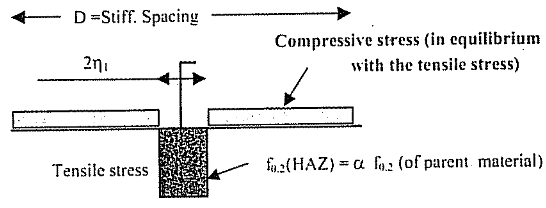


**Fig. 12: Residual stress across the HAZ**

For the transversal welds (C1 and C2), the residual stresses are acting perpendicular to the residual stresses of the longitudinal welding seams. The width of the field of compressive stresses in the plate is a problem, as it cannot be the entire length of the three-spans model. Therefore, they are considered to act only in the middle span of the model, between the two transversal beams (T2 and T3). The magnitude of the transversal residual stresses is determined in the same way as for the longitudinal ones.

*Weld positions and weld types (sensitivity assessment):* The results are presented in Fig. 12, Fig. 13 and Table 2. The tendency is the one already expected: the panel has a higher ultimate strength for welds B (extruded element) than for welds A (stiffeners welded on the plate).
The same trend is obtained with or without residual stresses (compare Fig. 5 to Fig. 13, Fig. 6 to Fig. 14 and Table 1 to Table 2). Ultimate strength reduction is a little bit larger with residual stress than without (excepted for Welds B).

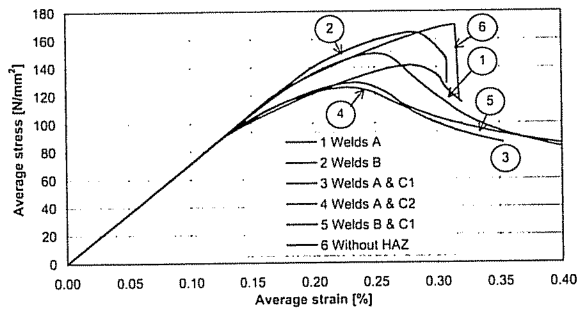


**Fig. 13: Effects of weld types with residual stresses (ISSC model and ISSC initial imperfections)**

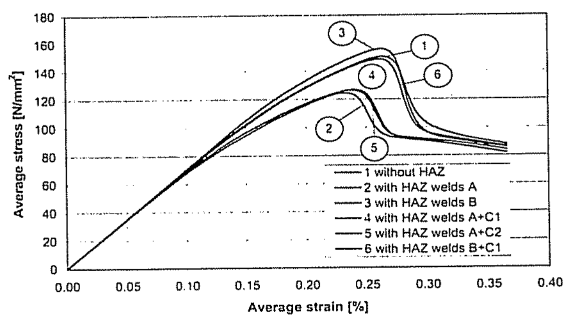


**Fig. 14: Effects of weld types with residual stresses (Standard model and Standard initial imperfections)**

Table 2: Effects of weld types with residual stresses – Reduction of maximum average stress to reference (without HAZ)

| Weld types | Reduction [%] A | Reduction [%] C |
|---|---|---|
| Welds A | 16.9 | 17.2 |
| Welds B | 3.0 | (-3.7)* |
| Welds A + C1 | 26.2 | 15.5 |
| Welds A + C2 | 24.1 | 15.8 |
| Welds B + C1 | 12.3 | 1.2 |
| **Without HAZ [N/mm²]** | 169.9 | 150.3 |

with **A** ISSC model and ISSC initial imperfections
**B** Standard model and Standard initial imperfections

* Such increase has to be confirmed by additional analyses

*HAZ width (sensitivity assessment):* Effect of the HAZ width combined with residual stresses was also assessed. The width of the HAZ is modified and it becomes, respectively, 2 $\eta_1$ =25, 50 and 75 mm for the plate, $\eta_2$=12.5, 25 and 37.5 mm for the stiffener. Fig. 15 shows the results for the configuration with Welds A (between the stiffeners and the plate) and Fig. 16 presents the results for Welds A+Weld C1.

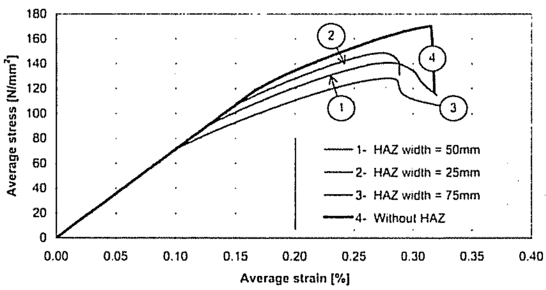


**Fig. 15: Influence of the HAZ width (2 $\eta_1$) (ISSC model and ISSC initial imperfections, Welds A, with residual stresses)**

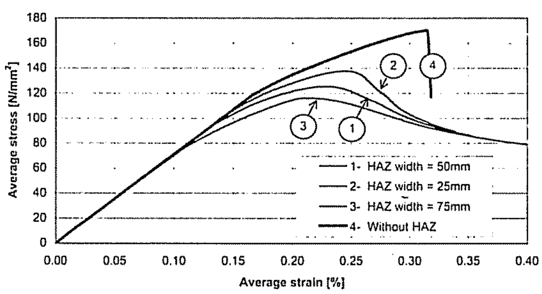


**Fig. 16: Influence of the HAZ width (2 $\eta_1$) (ISSC model and ISSC initial imperfections, Welds A and C1, with residual stresses)**

*Phase B5—yield stress in the HAZ*

Analyses were done to assess the effect on the ultimate strength of the variation of yield stress in the HAZ. Plate and stiffener material properties and yield stress outside of the HAZ do not change. These analyses concern the configuration with Welds A.

The initial material stress–strain curve in the HAZ is defined as "Sy(ref HAZ)". The modified curves considered to assess the effect of the yield stress in the HAZ are shown in Fig. 17. They are "Sy(ref HAZ)-10" up to "Sy(ref HAZ)+60", with increments in N/mm².

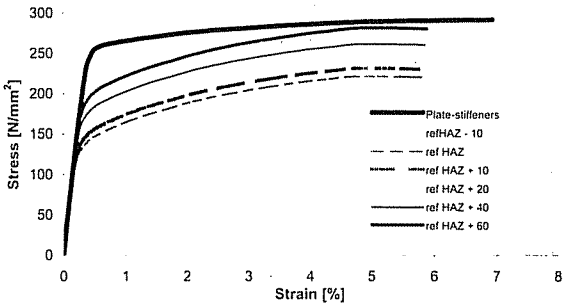


**Fig. 17: Modified material stress–strain curves in the HAZ (ISSC model and ISSC initial imperfections, Welds A)**

The ultimate strength does not vary linearly with the yield stress in the HAZ but almost linearly with its square root. So, the strength reduction due to yield stress variation may be assessed through the plate and column slenderness ratios of the panel that vary as the square root of the yield stress.

Fig. 18 shows that a reduction of yield stress in the HAZ of 10% induces an ultimate strength reduction varying from 5% to 2%. The first reduction of yield stress has larger effect than additional reductions.

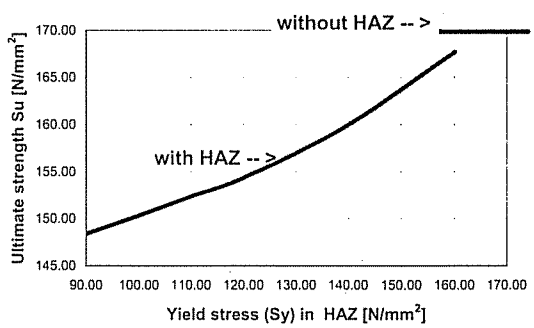


**Fig. 18: Variation of ultimate strength versus yield stress in the HAZ**

## Conclusions

### *Benchmark*

Contributors carried-out finite element analyses to assess the sensitivity on the ultimate strength of welding join types, HAZ width, initial panel deflection (amplitude and shape), residual stress, plate thickness and yield stress in the HAZ.

For the considered structures, the sensitivity analysis have provided quantitative assessments (Table 3):

**Table 3: Conclusions - Reduction of maximum average stress to reference (without HAZ)**

| | | | Reduction [%] A | Reduction [%] B | Reduction [%] C |
|---|---|---|---|---|---|
| Without residual stresses | Weld types | Welds A | 13.4–21.5 | 8.0 | 9.4 |
| | | Welds B | 1.3 – 9.1 | 5.4 | 1.1 |
| | | Welds A+C1 | 25.6-27.5 | 18.2 | 9.1 |
| | | Welds A+C2 | 22.1-23.4 | 19.6 | 8.9 |
| | | Welds B+C1 | 12.6-18.2 | 11.2 | 1.0 |
| | | Welds B+C2 | 18.1 | Not considered | |
| | HAZ width (Welds A) | $2\eta_1$ = 25 mm | 8.6 | Not considered | |
| | | $2\eta_1$ = 50 mm | 12.9 | | |
| | | $2\eta_1$ = 75 mm | 17.2 | | |
| | | $2\eta_1$ = 100 mm | 20.3 | | |
| | Initial deflection | w = 4 mm | 2.6 | Not considered | |
| | | w = 8 mm | 6.5 | | |
| | Yield stress in the HAZ | $S_{y.HAZ}$ - 10 | 1.3 | Not considered | |
| | | $S_{y.HAZ}$ + 10 | -1.4 | | |
| | | $S_{y.HAZ}$ + 20 | -2.7 | | |
| | | $S_{y.HAZ}$ + 40 | -6.4 | | |
| | | $S_{y.HAZ}$ + 60 | -11.6 | | |
| With residual stresses | Weld types | Welds A | 16.9 | Not considered | 17.2 |
| | | Welds B | 3.0 | | -3.7 |
| | | Welds A+C1 | 26.2 | | 15.5 |
| | | Welds A+C2 | 24.1 | | 15.8 |
| | | Welds B+C1 | 12.3 | | 1.2 |
| | HAZ width (Welds A) | $2\eta_1$ = 25 mm | 12.4 | Not considered | |
| | | $2\eta_1$ = 50 mm | 16.9 | | |
| | | $2\eta_1$ = 75 mm | 24.3 | | |
| **Without HAZ (reference) [N/mm²]** | | | 160:8 - 173.5 | 159.6 | 141.2 – 150.3 |

with A ISSC model and ISSC initial imperfections
B Standard model and ISSC initial imperfections
C Standard model and Standard initial imperfections

### *Recommendations*

In the considered analyses, the range of variation of the different parameters was imposed. It would be useful to assess the real variation and the uncertainity on these parameters, in particular, the yield stress in the HAZ and the width of the HAZ.

It seems that the parameters having the larger influence on the ultimate strength are the yield stress in the HAZ and the width of the HAZ. On the contrary the residual stresses and the initial deflection have a smaller influence on the ultimate strength of the studied aluminium stiffened panel.

Non linear finite element analyses remain heavy procedures to determine the ultimate strength of aluminium stiffened panels. Thus it is necessary to develop simplified tools derived from finite element analyses, as the Paik's formulae [Paik et al., 2003], to assess the ultimate strength of aluminium stiffened panels.

In the future, this sensitivity assessment has to be continued with the study of other parameters and panel configurations.

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