A98-31712

ICAS-98-7,7,3

A DESIGN AND TEST PROGRAMME INVOLVING WELDED SHEET-STRINGER COMPRESSION PANELS

A. Gibson* and S. G. Sterling**
Department of Aeronautical Engineering, The Queen's University of Belfast,
Belfast, BT9 5AG, Northern Ireland
*Postgraduate research student **Senior Lecturer

Abstract

In order to assess the potential savings in using welding as a joining process for airframe structures, test articles must be designed, manufactured and evaluated. The design/analysis phase must incorporate an allowance for the detrimental effects of welding on airframe type alloys and joint design must reflect the prevalent loading conditions. This paper focuses on the design/analysis of a flat, welded, stiffened panel loaded in compression and proposes methods for allowing for degradation of material properties in the heat-affected zones (HAZ's) surrounding the welded joints. The analysis follows the same procedure as that for a riveted panel with suitable modifications where required. The aim is to develop simple design rules and analysis methodology for this type of structure. Theoretical results show that, using the weldable 6013-T6 alloy, it is possible to achieve weight savings of up to 10% for the same overall performance as a riveted panel. In order to verify, or otherwise, the proposed analysis and predictions, it will be necessary to initiate a suitable test programme. A preliminary test stage is discussed and methods are proposed for determining actual values for the estimated variables which were used in the theoretical analysis.

Introduction

In the current economic climate facing the world-wide aerospace industry, reducing the costs of manufacture and assembly are becoming increasingly important issues for airframe manufacturers. Since joining processes at assembly account for a significant element of the time and cost involved in production, it follows that improvements in this area could play a major role in helping to meet the required reduction targets. Riveting has been the predominant joining process for metal airframe structures for many years and is a mature and well researched technology. The process has become highly automated with the introduction of NC riveting machines but it is now accepted that the potential for further improvements in this area is limited. Furthermore, mechanical fasteners have weight penalties both in themselves and in the nature of the designs which have evolved around them. These factors have led to considerable interest being shown in joining technologies which may provide a direct alternative to conventional mechanical fasteners in primary and secondary metal airframe structures. Welding is one such technology with the potential to realise cost and weight reductions.

Certainly the basic technology now exists with respect to advanced arc and power beam welding processes, and with respect to automated, robotic manufacturing cells as evidenced in the automobile industry. The challenge now is to address the major issues which surround the application of welding specifically to the design and manufacture of airframe structures.

It is reasonable to assume that the manufacturing issues will be successfully resolved and it is thus appropriate to begin to address issues specific to the design and analysis of proposed welded airframe structures. Riveted metal structures and accompanying stressing methods have evolved together over the years. Suitable methods for analysing and qualifying welded structures must now be developed.

It would be advantageous to be able to apply simple modifications to existing stressing procedures for riveted structures and apply them to welded structures regardless of the loading conditions. The possibility of this being the case will depend on the respective joint designs required for a particular loading condition. This paper presents methods of incorporating an allowance for welding effects into the design/analysis of a stiffened sheet-stringer panel subject to static compressive loading only.

The design drivers for the welded panel, on which the analysis focuses, are the structural performance of a baseline riveted panel which is representative of a section of a typical lower fuselage structure. Riveted panels and sub-components have been the subject of a test-programme at QUB, the results of which are available for use in this analysis[1]. Strength and weight targets along with properties for the materials used are given in the results section. The riveted panel analysis has been carried out in accordance with current stress office procedures[2-4]. The same analysis has been applied to the welded panel in order to maintain the same level of conservatism of design and to allow comparison of the two structures. Whilst fuselage panels are typically curved, this work is based on flat panels for simplicity of

21st ICAS Congress
13-18 September 1998
Melbourne, Australia

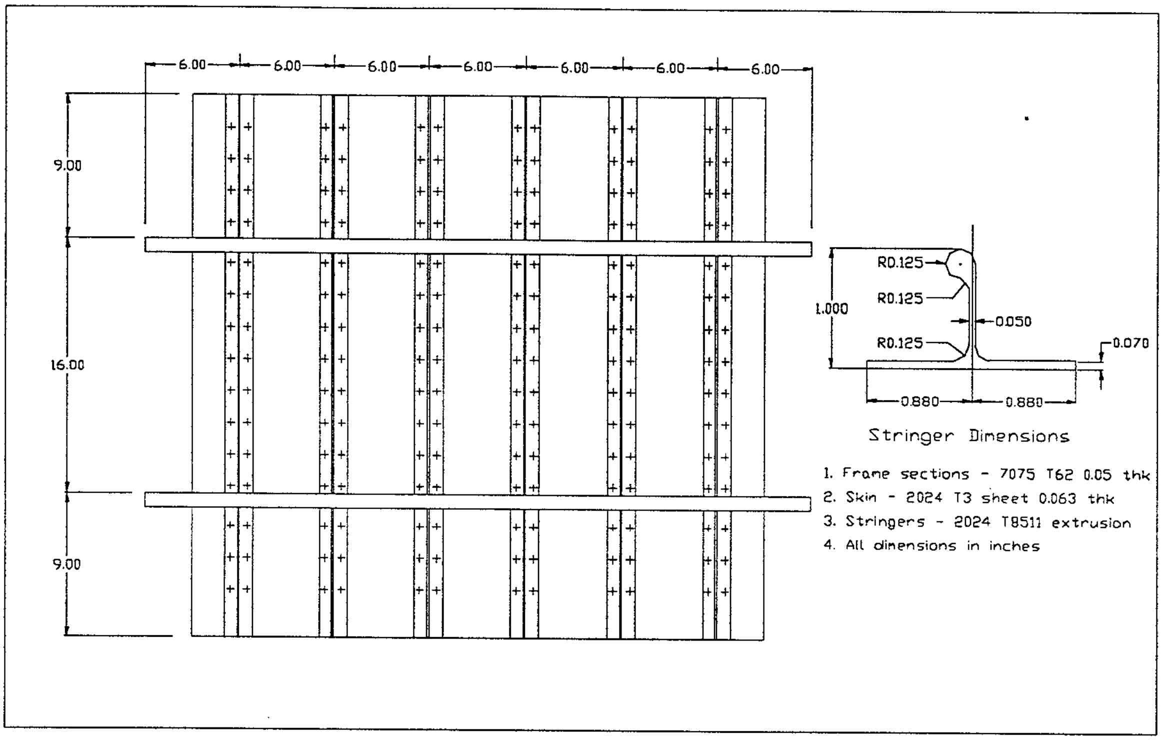

Figure 1. Riveted baseline compression panel geometry.

manufacture, test and analysis.

In this document the definition of the heat-affected zone (HAZ) is as given in BS8118 Part 1: 1991 Section 4.4.1, i.e. " For design purposes it is acceptable to approximate to the true condition by assuming that around each weld there is a zone, the HAZ, in which the strength properties are reduced by a constant factor, k_z. Outside this zone it is assumed that the full parent properties apply." The HAZ for our purposes is thus the whole width of affected material including the weld bead itself.

Riveted Baseline Compression Panel

Configuration and Materials

Figure 1 gives the riveted baseline compression panel geometry. The panel consists of two frame segments at 16" pitch, six identical extruded stringers of bulbed-T configuration at 6" pitch and a clad skin of uniform thickness. Skin-stringer rivet pitch is approximately 1.77".

Analysis Procedure

The baseline panel was designed to exhibit skin local buckling at relatively low load (approx. 50% limit load). As such, failure occurs in the post-buckled regime with sub-component tests showing failure in combined local/flexural buckling of the stringer. In the post-buckled regime the analysis assumes an "effective" width of skin works with each stringer in carrying load up to the point of failure. This is discussed in more detail in subsequent sections, in particular the effect on the proposed welded panel analysis methods. A stringer plus its effective skin is considered as acting as a column or strut with pinned ends and a length equal to the frame spacing. The following is a brief summary of the steps performed in the analysis of the compression panel:-

1. Determination of skin local buckling stress.
2. Determination of stringer component crippling stresses (web, bulb, flanges).
3. Determination of stringer overall crippling stress.
4. Determination of stringer (plus effective skin) failure mode and stress.
5. Determination of panel load at the above steps.

It is not intended to give a detailed discussion on the theory behind compression panel analysis in this paper. The aim is to propose modifications to the analysis as it stands in order to make it suitable for use with welded structures.

Welded Compression Panel

Stringer Configuration and Attachment

Several options are possible regarding the configuration of stringers and any typical type could potentially be used. Attachment via welding should allow weight reductions over riveting through elimination of attachment flanges, rivets and sealant. Improved designs should be possible bearing in mind the unique method of attachment that welding can offer. Figure 2 shows some possible attachment details. These joints, with suitable dimensions, could be produced using any of the previously mentioned welding processes.

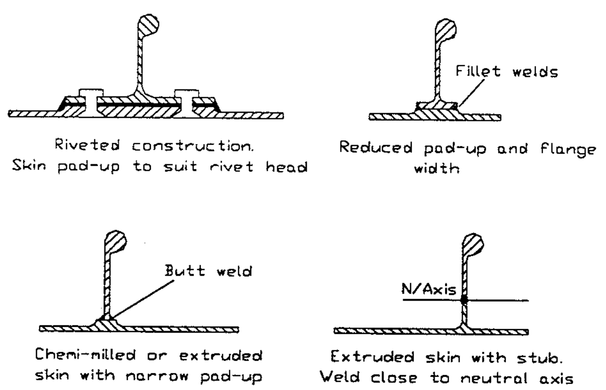

Figure 2. Possible weld attachments

Figure 3 shows the configuration of the stringer types selected for a welded compression panel considered within this paper. The blade and lipped-blade types are possibly the most economical from a manufacturing point of view. Attachment in this instance would be via a weld on each side of the stringer (producing a butt joint) and would require a small pad-up on the skin. Penetration of the weld through to the outside of the skin is to be avoided.

Allowance for HAZ

In the proposed methodologies, the welded joints have been treated as integral and the stress analysis performed as per the riveted panel but with an allowance being made for the degradation of material properties in the HAZ. In the case where skin and stringer are initially of the same parent material, a welded member then comprises two different materials, i.e. parent material and HAZ material. While the elastic modulus of the material may not be affected greatly there will certainly be a difference in the plastic regions of the stress-strain curves for the two materials. This will have an effect on the strength of the member since, at failure, some material will be working at its yield stress, i.e. in the plastic region, with the yield stress for the HAZ being lower than the parent material value. The effects of plasticity can be allowed for through use of the tangent modulus which, for a given strain, will again differ for the two materials. Furthermore, in the analysis it is necessary to determine section properties of the member cross-section and again these are affected by the fact that the member is composed of two different materials. It is advocated that an allowance for these differences, however small, must be made and the effect on the strength of the member quantified. Two alternative methods for dealing with the HAZ are proposed here:

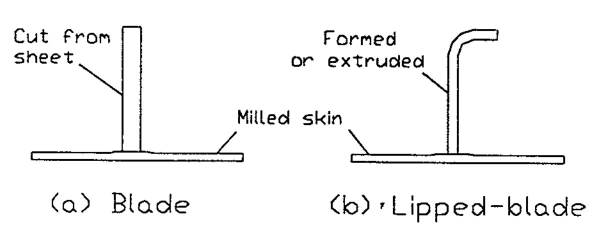

Figure 3. Stringer types for analysis.

(i) Using "equivalent" sections

The thickness of the member in the HAZ may be reduced by a constant factor, e.g. k_z say, as shown in Figure 4. This factor, k_z, will be related to the degree of degradation of material properties in the HAZ and is taken as the ratio of HAZ material yield stress to parent material yield stress. The cross-sectional area and sectional properties of this reduced member are then used in the analysis along with parent material properties. It is proposed that this reduced member composed of parent material is equivalent to the actual member composed of both parent material and HAZ material. The width of HAZ and factor k_z will need to be determined experimentally. They will depend on parent material, welding process and welding parameters.

(ii) Using "hybrid" material properties

The member as a whole (stringer plus effective skin) is treated as having material properties which lie somewhere between those of the parent material and those of the HAZ as shown in Figure 5. The HAZ material σ-ε curve is related to the parent material σ-ε curve by the ratio k_z as discussed in the preceding section. The hybrid material properties can be estimated from these two curves knowing the ratio of HAZ material to parent material but this will need to be verified experimentally. The theoretical hybrid σ-ε curve can be plotted as follows; for a given strain value the corresponding hybrid (or average) stress, *Fh*, is determined from Equation 1.

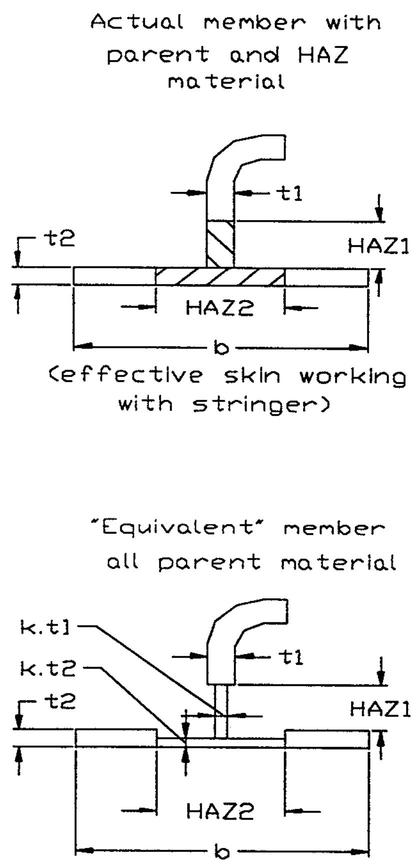

Figure 4. "Equivalent" section method.

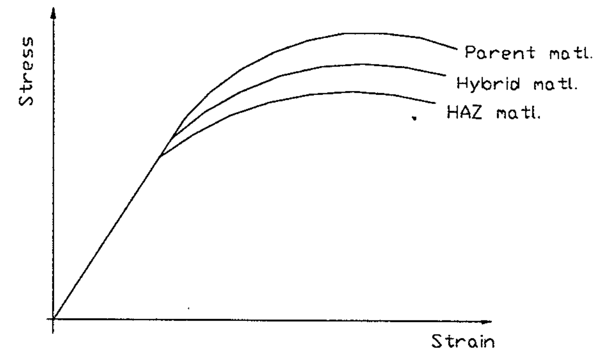

Figure 5. "Hybrid" material method.

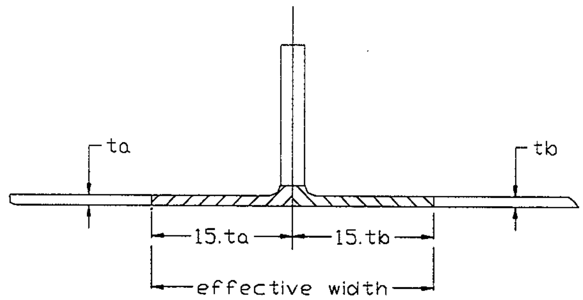

Figure 6. Effective width of skin.

$$Fh = \frac{(Fp.Ap) + (Fz.Az)}{Ap + Az} \qquad (1)$$

where
Fp = parent material stress at the given strain
Fz = HAZ material stress at the given strain
Ap = area of parent material in the member
Az = area HAZ material in the member

Effective skin width

In this paper, the effective skin working with a stringer is taken to have a width equal to 15 times the skin thickness on either side of the attachment line as shown in Figure 6. This is a relatively common value used for stress analysis purposes and on comparison with other techniques gives quite good results. Using a fixed value for the effective width simplifies the analysis when using "hybrid" properties since the ratio of HAZ material to parent material in the welded member is then also fixed. It also reduces the degree of iteration required in determining the failure stress of the member (see following section).

Analysis

(i) Skin local buckling

Buckling occurs at a relatively low stress for thin skin panels (in the elastic region) and in this analysis will not be affected by the fact that the plate edges are welded rather than riveted. In both cases the plate edges are assumed to be simply supported. Considering the dimensions in this case, it is unlikely that the HAZ at the edges of a plate would extend far enough to have any real effect on the buckling stress. Hence, the skin local buckling stress, F_b, is determined in the same manner as for the riveted structure using Equation 2 and assuming no degradation of plate material properties.

$$F_b = KE_t\left(\frac{t}{b}\right)^2 \qquad (2)$$

where
K = buckling coefficient depending on plate aspect ratio and edge support conditions
E_t = tangent modulus of the material at the calculated buckling stress and allows for plasticity effects
t = plate thickness
b = plate width (loaded edges)

(ii) Stringer crippling

The initial buckling stress, F_{bn}, of an element of a stringer section, i.e. web or flange, is calculated using either Equation 3 or Equation 4 as follows:-

$$F_{bn} = 3.62 E_t \left(\frac{t_n}{b_n} \right)^2 \quad (3)$$

for both edges simply supported, or

$$F_{bn} = 0.58 E_t \left(\frac{t_n}{b_n} \right)^2 \quad (4)$$

for one edge simply supported, one edge free,
where
E_t = tangent modulus of the appropriate material (parent or hybrid) at the calculated buckling stress and allows for plasticity effects
t = element thickness
b = element width
and subscript n refers to element n

The blade stringer is assumed to have one edge simply-supported (the attached edge) and the other edge free. The lipped-blade stringer is considered to be simply-supported at the attached edge and either simply-supported or free at the other edge depending on the dimensions of the lip. Care is taken in the design to ensure that the lip does offer simple-support as this obviously increases the buckling stress.

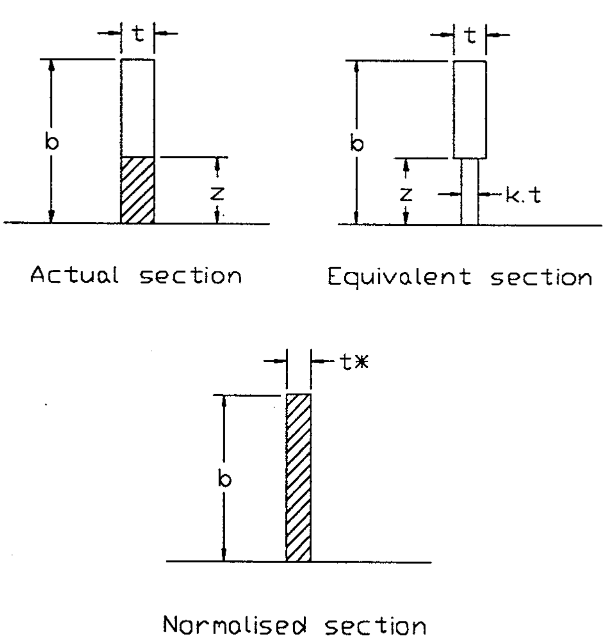

Figure 7. "Normalised" section.

Figure 7 shows the estimation of an element thickness and width when using the equivalent section method of allowing for the HAZ. The normalised thickness, t^*, is obtained by keeping width b constant and equating the area of the normalised section to that of the equivalent section, Equation 5.

$$b.t^* = (b - z).t + (z.k.t) \quad (5)$$

F_{bn} is then computed using b and t^* along with the parent material properties. If using the hybrid material properties for analysis, then b and t are unchanged. Hybrid material properties will be determined according to the ratio of HAZ material area to parent material area in the member. The ratio will be constant since a fixed width of effective skin is assumed as discussed previously.

The crippling stress, F_{ccn}, of an element is then computed using Equation 6.

$$F_{ccn} = \left(F_{cy} . F_{bn} \right)^{1/2} \quad (6)$$

where F_{cy} = appropriate material yield stress.

The overall crippling stress for the section is then computed using Equation 7 using the appropriate value for t.

$$F_{cc} = \frac{\sum b_n . t_n . F_{ccn}}{\sum b_n . t_n} \quad (7)$$

Failure due to overall crippling is unlikely except for very short column lengths. Failure due to local buckling and crippling of an element of the stringer in combination with flexing of the stringer may well occur however and this is dealt with in the following section.

(iii) Stringer failure

Failure for this particular configuration of compression panel is assumed to occur due to combined flexural and local instability of the stringer. The skin provides considerable restraint against flexure about an axis perpendicular to the skin even though buckling of the skin between stringers has occurred. It is thus necessary to check for failure about one axis only and this is accomplished using the Secant formula, Equation 8. This allows the critical buckling stress, F_a (the average stress on the strut at failure), to be computed. Failure is assumed when the stress in the most compressed fibres reaches its maximum allowable value. For example, if flexing occurs in a riveted member such that the outer skin fibres are most compressed (outside skin concave), failure is assumed when the stress in those fibres reaches the material yield stress, the attached flange crippling stress or the inter-rivet buckling stress, whichever is the lowest. For the welded panel, considering the stringers being analysed, failure on the skin side is assumed when the stress in the fibres reaches the material yield stress or the crippling stress of the attached stringer element, whichever is lower. If flexing is in the opposite direction (outside skin convex), for example for the lipped-blade, failure is assumed at the lower of the material yield stress and the lip crippling stress.

$$F_{\max} = F_a\left[1+\frac{e}{c}\sec\frac{l'}{2k}\left(\frac{F_a}{E_t}\right)^{1/2}\right] \qquad (8)$$

where

F_{max} = maximum stress in extreme fibre = F_{allow} at failure

F_a = average stress in the strut at failure

E_t = tangent modulus at stress F_a

e = total eccentricity (including bow, manufacturing and loading eccentricity)

c = k^2 / y

k = radius of gyration of section

y = distance from neutral axis of section to extreme fibre

l' = effective length of strut

The section properties in Equation 8 are calculated for the stringer and its attached effective skin and will depend on the method being used.

If using the equivalent section method with the Secant formula, section properties of the reduced section are used along with parent material properties. If using hybrid material properties, (which will be as determined previously for crippling analysis), section properties are those of the actual section. Again, use of a fixed width of effective skin is most beneficial.

Solution of the Secant formula is an iterative process and it is necessary to check for failure in both directions of flexure in order to determine the critical stress, i.e. skin concave and skin convex.

Design/Analysis automation

The foregoing analysis procedure has been automated using a PC-based spreadsheet programme incorporating Visual Basic modules. Using estimates for the unknowns, i.e. HAZ width, k_z etc., allows various design iterations to be performed. In this manner a theoretical comparison between a welded and a riveted panel can be made. Furthermore, we can identify the maximum allowable values for HAZ width and k_z in order to produce a panel of determined strength and weight.

Design iterations and results

Design iterations were performed to determine the dimensions for stiffened welded panels which would be comparable in weight and strength to the riveted baseline panel. Estimations for HAZ width and reduction factor, k_z, were used. Both the "equivalent" section and "hybrid" material methods were used in the analysis and showed good correlation. Welded panel designs were based on 6013 T6 material (for both stringers and skin) which is considered weldable and of relatively high strength. This material, or a derivative of it, may well have future potential in airframe manufacture.

Material	E (msi)	Fcy (ksi)	Fn (ksi)	m	μ
2024 T8511	10.86	68.60	62.84	24	0.33
2024 T3	9.58	43.40	36.71	10	0.33
6013 T6 parent	10.51	55.92	50.66	23	0.33
**6013 T6 HAZ	10.51	44.74	40.12	23	0.33
**6013 T6 hybrid1	10.51	50.83	45.73	22	0.33
**6013 T6 hybrid2	10.51	50.74	45.61	22	0.33

Note: hybrid1 refers to blade stringer analysis
hybrid2 refers to lipped-blade stringer analysis
** theoretical values

Table 1. Material compression test results.

Riveted panel results[1]

Stringer type	Bulbed-tee
Stringer material	2024 T8511 extrusion
No. of stringers	6
Stringer pitch (in)	6
Skin material	2024 T3 clad sheet
Panel weight (lb)	5.905
Failure load (tons)	33.276

Note: panel weight refers to a 16" length of panel and does not include frames or sealant.

Table 2. Riveted panel data.

Welded panel results

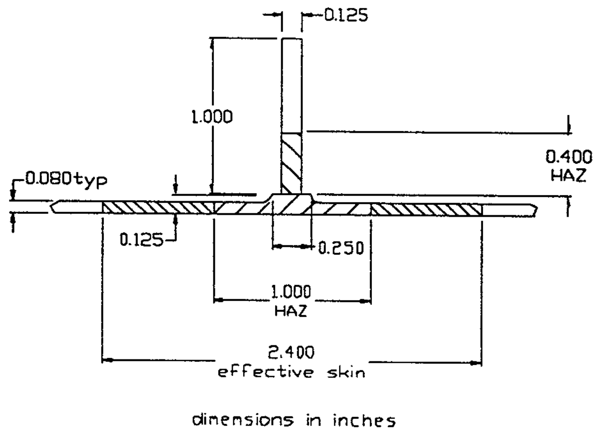

Figure 8. Blade stringer geometry.

Stringer type	Blade
Stringer material	6013 T6 sheet
No. of stringers	6
Stringer pitch (in)	6
Skin material	6013 T6 sheet
Factor k_z	0.8
Panel weight (lb)	5.798
Failure load1 (tons)	33.732
Failure load2 (tons)	33.648

Note: Failure load1 refers to analysis using "equivalent" section method. Failure load2 refers to analysis using "hybrid" properties method.

Table 3. Blade panel data.

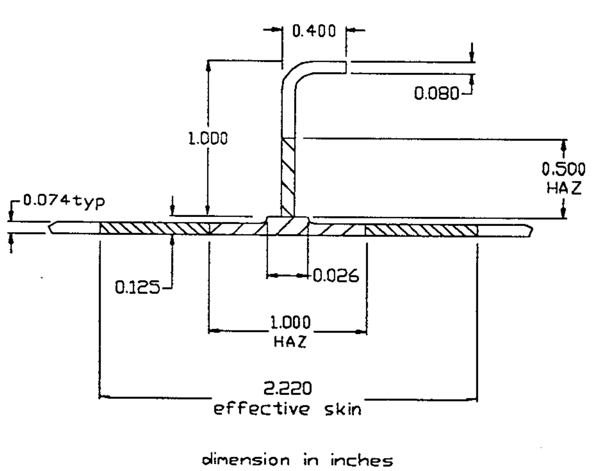

Figure 9. Lipped-blade stringer geometry.

Stringer type	Lipped-blade
Stringer material	6013 T6 sheet
No. of stringers	6
Stringer pitch (in)	6
Skin material	6013 T6 sheet
Factor k_z	0.8
Panel weight (lb)	5.296
Failure load1 (tons)	34.056
Failure load2 (tons)	33.786

Table 4. Lipped-blade panel data.

Results summary

Panel Type	Failure load (tons)	% Increase on riveted panel
Riveted	33.276	
Blade	33.690	+1.24
Lipped-blade	33.921	+1.94

Note: Welded panel failure load is taken as the average of the two analysis methods.

Table 5. Summary of panel failure loads.

Panel Type	Weight (lbs)	% Increase on riveted panel
Riveted	5.905	
Blade	5.798	-1.81
Lipped-blade	5.296	-10.31

Table 6. Summary of panel weights.

The theoretical results show that using a relatively strong weldable material such as 6013 T6, it should be possible to produce stiffened compression panels with similar performance to and of equal or less weight than a riveted counterpart. The truth of this of course depends on the validity of the analysis performed and this can only be verified through testing. The variables used are thought to be representative of average results for welded joints of this type and give an indication of the level of quality required. It is considered that laser welded joints could be produced with much narrower HAZ width than that assumed in this analysis. Using the correct filler wire and with highly weldable material, it is also feasible that the HAZ material yield stress of 80% of the parent value assumed here could be achieved. Probably a more realistic value at present would be 70%. This could still be tolerated by increasing the dimensions of the joint bearing in mind there is some leeway with regard to weight. At present, the two methods of allowing for degradation in the HAZ agree quite well with both showing failure in the same mode as the riveted panel, i.e. outer skin convex.

The same analysis was performed for the blade and lipped-blade stringers assuming no degradation of material properties, i.e. a truly integral panel. The results showed that welded blade panel failure load was around 4% less than its integral counterpart while, for the lipped-blade, there was a 5- 6%. reduction.

Test programme

A test programme has been developed in order to verify, or otherwise, the preceding analysis proposals. In the first instance, testing centred around welded plates will determine values for HAZ width and k_z, along with hybrid σ-ε curves for various ratios of HAZ to parent material. Following this, compression panels and smaller sub-components designed to these parameters will be manufactured and tested. The Stage 1 tests are discussed in the following section.

Stage 1 test programme

This stage will determine values for HAZ width and k_z for bead-on-plate, CO_2 laser welds in 6013-T6 sheet. Sheet thickness of 0.080" and 0.125" will be used. σ-ε curves for various plate widths with a central weld bead, and hence various ratios of HAZ to parent material, will be plotted and compared to theoretical curves. These plates (without full weld penetration) are intended to be representative of the skin of the welded panel.

(i) Determination of HAZ width

A common method of determining the width of the HAZ is by measuring the material hardness across a welded area. This can be applied to the face of the welded plate or alternatively a micro-hardness test can be applied to

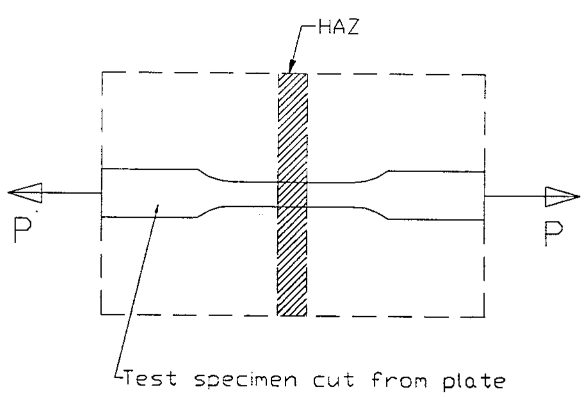

Figure 10. Typical test specimen orientation.

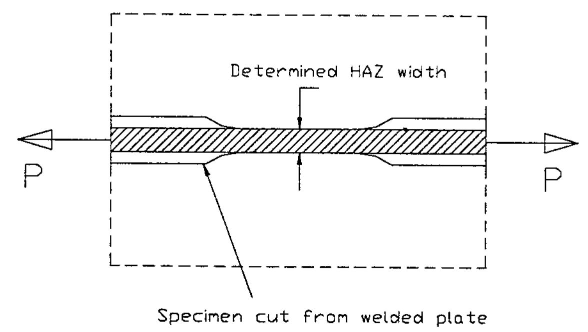

Figure 11. Proposed specimen orientation.

the cross-section. A resulting plot of hardness versus distance from weld will allow the extent of the HAZ to be identified. The value will be specific to the welding process and parameters and to the material used. This is a well documented procedure and no further discussion is necessary.

(ii) Determination of k_z

Testing will be carried out using tensile specimens and the determined relationship between parent material and HAZ material, i.e. k_z, assumed to apply in compression also. Available information concerning material properties in the HAZ has usually been determined for tensile test specimens with loading applied transverse to the weld direction, Figure 10. The results given thus relate to the weakest material in the zone. In order to determine the HAZ material properties for the analysis proposed in this paper, tests will be performed on specimens of width equal to the HAZ width and with the applied loading in the direction of the weld, Figure 11. Stress is taken as applied load divided by the original cross-sectional area of the specimen. Results obtained will relate to average properties in the HAZ and as such are more realistic for this analysis. The value of k_z obtained will obviously be particular to the welding process and parameters, parent material and joint type, i.e. bead-on-plate. Having determined the parent material and HAZ material σ-ε curves, it will be possible to produce theoretical hybrid curves for given ratios of material areas as discussed previously. Specimen geometry and dimensions are further discussed in the following section.

(iii) Determination of hybrid material σ-ε curves.

In order to determine the accuracy of the theoretical hybrid curves, it is necessary to test specimens of various widths and hence various ratios of HAZ to parent material. In this programme, widths of 4", 3" and 2" will be tested. For a given width, stress is taken as the applied load divided by the original cross-sectional area of the specimen. Obviously the specimens will be of non-standard dimensions and this requires some investigation. For practical purposes, a maximum test specimen length of 15" is allowable and in order to average out any welding defects such as porosity and cracks, a non-standard gauge length of 6" is to be used. This has necessitated the development of special-purpose extensometers.

Due to the non-standard dimensions of the test specimens it is impossible to obtain uniform strain across the width of the specimen over the specified gauge length. This is due to interference effects from the clamped ends of the plate. This could not be eliminated due to the restriction on specimen length. Non-linear FE analysis was used to simulate the tensile test on an unwelded plate and hence aid in the definition of the specimen profile giving the least strain measurement error. The parent material σ-ε curve derived during standard tensile testing was used for the analysis and various specimen profiles were modelled with varying degrees of success. The geometry of the two profiles giving the best results is given in Figure 12. Of these, the parallel plate is best overall for the range of widths to be tested. The strain across a 4" parallel plate at various distances from the horizontal centreline is shown in the following figures. Strain was taken as nodal deflection in the loading direction divided by the original distance of the node from the horizontal

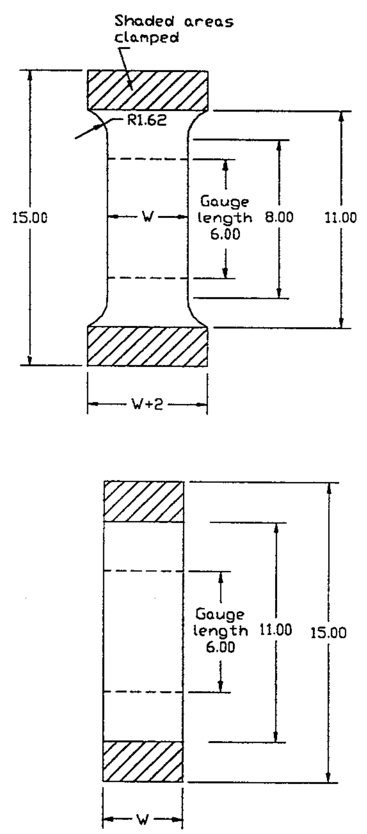

Figure 12. Tensile specimen profiles.

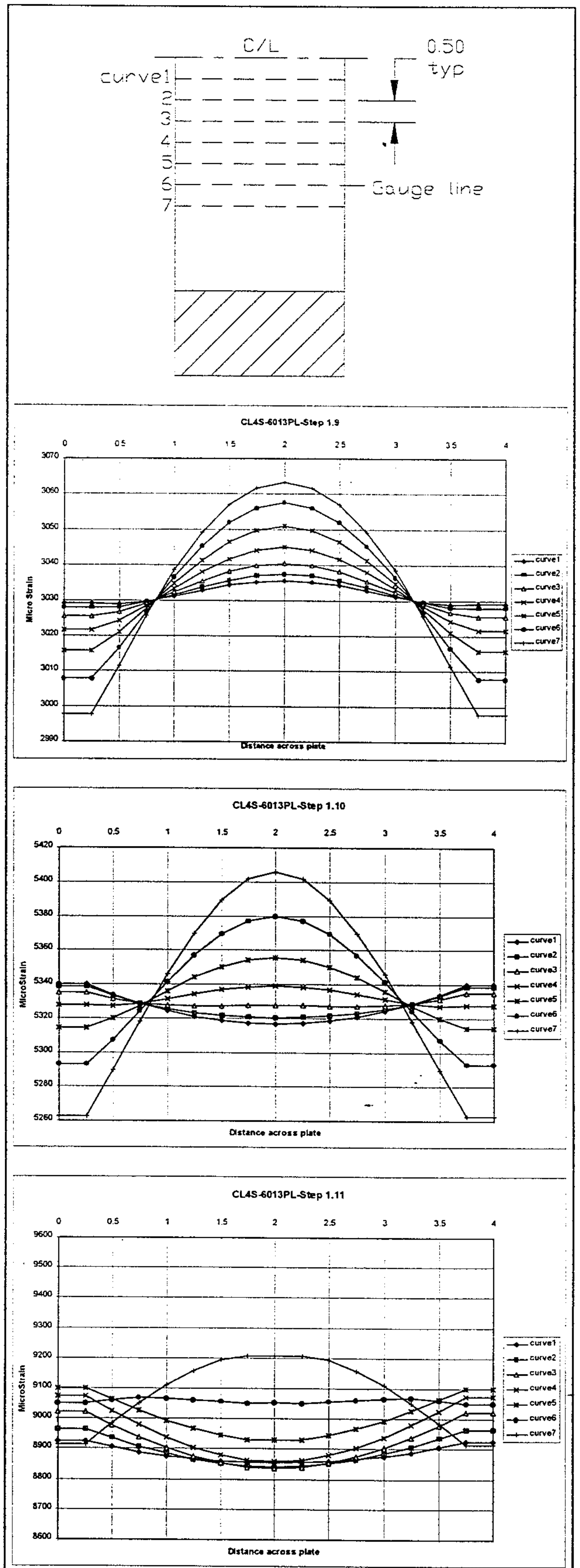

Figure 13. FE strain prediction - 4" plate.

centreline of the plate. The pattern shows that reasonably good experimental strain readings can be obtained by locating the extensometer midway between the vertical centreline and the edge of the plate. This method will be used to plot hybrid σ-ε curves for welded plates of the widths stated previously. σ-ε curves for unwelded plates of the same widths will also be plotted and used as a datum against which to determine the effect of the HAZ on the material properties.

Conclusion

The design and analysis of welded airframe structures will require the development of suitable stressing methods which will take into account the effect welding has on the properties of typical airframe alloys. Two methods of allowing for degradation in the analysis of a stiffened compression panel are proposed here. These have been demonstrated in the analysis of a welded panel designed to the criteria of equal load-carrying capability and similar weight to a typical riveted fuselage panel. Theoretical results have shown weight savings of up to 10% may be possible using the weldable, relatively high strength alloy 6013 in the T6 condition.

The predictions and proposed analysis can only be verified through relevant testing. The first stage of a test programme developed for that purpose has been described here.

In this paper it has been assumed that successful manufacturing will be possible and no allowance has been made at this stage for residual stresses and defects such as cracks, porosity and distortion. It is not possible to simultaneously address every issue or consider every possible loading condition and subsequent research will need to be initiated pending encouraging early results.

References

1. Lynch, C.J.: A Finite Element Study of the Postbuckling Behaviour of a Flat Stiffened Panel. The Queen's University of Belfast, Department of Aeronautical Eng., April 1998
2. ESDU: Structures Sub-series
3. Bruhn, E.F.: Analysis and Design of Flight Vehicle Structures. Tri-State Offset Company, USA
4. Timoshenko,S. and Gere, J.M.: Theory of Elastic Stability. McGraw Hill Book Company, 1961
5. Armoa, F.: Investigation of GMAW Characteristics of Alloy 6013. Alcoa report, Welding Aluminium Alloys, File item 39
6. ASM Handbook (1994): Aluminium and Aluminium Alloys. ASM Speciality Handbook
7. British Standard BS 8118: Part 1: 1991. Structural Use of Aluminium
8. Cross, C.E.: Weldability of Al-Li alloys. Proceeds 2nd Int. Al-Li Conference, 1983
9. Ellis, M.D.B. and Spiller, K.R.: Gas Shielded Fusion Welding of Aluminium Alloys - A Review of Techniques. Welding and Metal Fabrication, 1993
10. Lang, A. and Bergman, H.W.: Mechanical Properties of Laser Welded Aluminium Alloys. Lehrstuhl Werkstoffwissenschaften 2, Erlangen FRG
11. Le Poac, P. et al: Mechanical Properties of Electron Beam Weldings in 8090 Alloy. Journal de Physique, 1987
12. Metzger, G.E. Some Mechanical Properties of Welds in 6061 Al-alloy Sheet. Welding Journal Research Supplement, Oct. 1967
13. Neye, G. and Heider, P.: Laser Beam Welding of Modern Al-alloys for the Aircraft Industry. Daimler Benz Aerospace Airbus GmbH, Bremen
14. Neye, G.: The Concept of Laser Beam Welding for Fuselage Panel Structures. Daimler Benz Aerospace Airbus GmbH, Bremen
15. Norrish, J.: Advanced Welding Processes. Institute of Physics, Bristol, 1992
16. Rendigs, K.H.: Aluminium Structures Used in Aerospace-Status and Prospects. Materials Science Forum Vol. 242 (1997) pp. 11-24
17. Thorstensen, B.: Laser Welding of Aluminium. Industrial Laser Handbook, Norway, 1992-3