The application of finite element methods to the analysis of welded aircraft fuselage panels

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Abstract

In a design and test project aimed at investigating the compressive buckling strength of welded aluminium alloy fuselage panels, analyses were performed using conventional stressing methods incorporating modifications to allow for the loss of strength which occurs in the heat-affected-zone (HAZ) which surrounds a weld made in this material. Due to inherent conservatism and necessary simplifications, it was not possible to determine if the modified analysis methods were valid or accurate. In light of this, simple FE analysis methods were also used to predict the strength and behaviour of the test specimens used in the project and, thus, to determine if FE methods offer the potential for more accurate analysis of this type of structure or even the potential as a first cut design tool. The modelling techniques used for the welded specimens and the comparison between FE predictions, analytical predictions and test results are discussed in this paper.

1 Introduction

The design of a baseline panel formed an integral part of the welded panel research project. The design drivers for the welded baseline panel were overall dimensions and layout, ultimate strength and weight. These were based on a section of the lower fuselage structure of a currently produced business jet. Several test specimens representing sections of the baseline panel were subsequently manufactured using the aluminium alloy 6013-T6 and laser beam welding. The specimens featuring in this report include “sub-panels”, i.e. panels consisting of one stringer and a given width of skin material, and short-column crippling specimens. The use of sub-panels enabled the work to proceed in manageable steps and allowed experimental evidence to be generated. They also
provided a vehicle by which the welding technology could be demonstrated in an economical manner. By the same token, the design of the baseline panel provided a means by which realistic test articles could be identified. It should be noted that, whilst fuselage panels are typically curved, the panels discussed in this paper were flat for simplicity of manufacture and testing.

In order to complete the design/analysis of the baseline welded panel, it was necessary to make modifications to conventional stressing methods to allow for the loss of strength in the HAZ surrounding a welded joint. To apply these modifications, it was necessary to make various assumptions and simplifications regarding the state of the material around a weld. These are discussed later. While the test specimens performed well, due to the simplifications and the inherent conservatism in conventional stressing techniques, it was not possible to determine if the analyses performed were accurate or valid. Furthermore, these conventional methods cannot easily allow for other effects of welding, such as residual stresses and distortion, which may be influential in the behaviour of welded aluminium alloy structures. In light of this, simple FE methods were also used to predict the strength and behaviour of the test specimens, the results being used to determine if FE methods have potential as a suitable analysis tool for this type of structure.

The overall FE modelling strategy used was based on that developed in a parallel project involving the buckling analysis of conventional riveted fuselage shell structures. The models utilised shell elements and incorporated the same simplifications mentioned above regarding material properties in the HAZ. The simple models did not incorporate any allowance for residual stresses or for distortion.

![Figure 1: Material zones around a welded joint](image)

2 Baseline panel design/analysis

To perform the analysis of the welded panel, it was necessary to simplify the situation regarding the condition of the material in the HAZ. The post-welded state of the HAZ will range from the solution treated state to overaged. For analysis purposes, material strength in the HAZ was assumed to be uniform but of a lower value than the surrounding parent material, i.e. it was assumed that around a weld there is a zone, the HAZ, in which the strength properties are reduced by a constant factor, $k_z$, and that outside this zone the full parent material properties apply. The factor $k_z$ will be discussed shortly.
The situation surrounding a welded stringer is assumed to be as shown in Figure 1. The joint consists of parent and HAZ materials, the HAZ material properties being an average of the actual non-uniform properties in the HAZ, and related to the parent properties via the factor $k_e$. Full details of how the design and analysis of the baseline welded panel was performed are given by Gibson [1].

3 Sub-panel test specimens

The overall layout of the sub-panels which were derived from the baseline panel design and subsequently manufactured for testing were 11.24" wide by 17" long. A 0.5" thick block of the low melting point alloy, Cerrobend, was cast onto the ends of the specimens, leaving a column length of 16" between the inner faces of the Cerrobend. The Cerrobend was intended to provide fixed end conditions for the specimens. The unloaded long edges of the sub-panels were supported by stiffened steel bars which overlapped the skin by 0.5". Sufficient clearance was maintained between the support bars and the Cerrobend in order to prevent the edge support bars picking up any end load. These support bars were considered to give simple support to the skin plate.

Two stringer types featured in the design, i.e. a blade and a lipped stringer, details of which are shown in Figure 2. The identity numbers given to the blade stringer and lipped stringer sub-panels were ST3BF and ST3LF respectively.

It can be seen that a pad-up is required under each stringer for attachment purposes. Also shown in Figure 2 are the HAZ widths used in the analysis for the two configurations. These values were based on the results from tests on welded plates [1]. The factor $k_e$ is taken as the ratio of the 0.2% proof stress of the HAZ material to the proof stress of the parent material for a particular thickness of sheet. A value of $k_e = 0.8$ was used throughout the various analyses and, again, this was derived from the tests on welded plates.

Even though the Cerrobend was intended to provide fixed end conditions, analyses were performed for both fixed and simply supported end conditions. Similarly, while the edge support bars were intended to provide simple support, both simply supported and fixed end conditions were analysed. The condition at
the stringer joint line was taken as simply supported in all cases. This provided upper and lower bounds for the predictions for buckling load and failure load. The cases analysed and the applied edge conditions are listed in Table 1. Cases 1A* and 2A provide the lower and upper bounds respectively, while Case 1A provides for the assumed conditions. For each case, the skin buckling load and failure load were predicted. Failure was assumed to be due to combined flexure/local buckling of the stringer which proved to be the case on testing.

4 Short column crippling specimens

These were essentially "T" sections which were machined from each configuration of sub-panel. The blade specimen was 2.25" wide by 5" high as shown in Figure 3. It was given the identity number TBCLAS. The lipped specimen was 2.5" wide by 5" high and given the identity TLCLAS. The main purpose of this test stage was to observe the behaviour of a localised area of a welded joint when subjected to compressive loading. Specimen ends were again cast in Cerrobend and subsequently machined flat and parallel to the required dimensions. The edges of the skin were left free with no support being provided, i.e. as free flanges.

![Figure 3: Short column crippling specimen - TBCLAS](image)

It was expected that local buckling of the flanges and/or stringer elements would occur, followed immediately by overall section crippling, i.e. short-column crippling, without any flexure. Preliminary tests however proved otherwise and the blade specimens failed in what appeared to be a torsional mode. Hence, for completeness, both crippling and torsional buckling were analysed. The crippling analysis was performed for both simple support and fully fixed conditions at the loaded edges, while the torsional buckling analysis was performed for fully fixed conditions on the loaded edges only. The cases are listed in Table 2. All sheet material properties used in the analyses are listed in Table 3. The properties used
for the skin material for all specimens were those for the 0.125" thick sheet, since all skin elements were milled from this thickness of sheet.

5 Test procedure

Compression testing of the various specimens was performed using a 25 tonf (250 kN) hydraulic testing machine. The machine was manually controlled via a jack load valve. The rate of load application could be monitored via a load display unit and maintained at a desired rate quite accurately. Load measurement and displacement measurement (end shortening between platens) were logged continuously to a data acquisition unit for the duration of each test. These data were subsequently downloaded to a PC based spreadsheet program for further processing. Test results which are presented here consist of load-displacement curves. These are used as a basis for assessing the accuracy of the theoretical predictions and the FE predictions. From these test curves, the stiffness, buckling load and failure load of a specimen can be identified.

Table 1. Sub-panel analysis cases

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Condition at loaded edges</th>
<th>Condition at unloaded edges</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>FF</td>
<td>SS</td>
</tr>
<tr>
<td>1A*</td>
<td>FF</td>
<td>FF</td>
</tr>
<tr>
<td>2A</td>
<td>SS</td>
<td>SS</td>
</tr>
</tbody>
</table>

Table 2. T-section analysis cases

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Condition at loaded edges</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>FF</td>
</tr>
<tr>
<td>2A</td>
<td>SS</td>
</tr>
</tbody>
</table>

Table 3. Material properties used for analyses

<table>
<thead>
<tr>
<th>6013 – T6 aluminium alloy compression properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent material</td>
</tr>
<tr>
<td>t = 0.125&quot;</td>
</tr>
<tr>
<td>E (ksi)</td>
</tr>
<tr>
<td>m</td>
</tr>
<tr>
<td>$f_y$ (ksi)</td>
</tr>
<tr>
<td>$f_t$ (ksi)</td>
</tr>
<tr>
<td>$f_z$ (ksi)</td>
</tr>
<tr>
<td>ν</td>
</tr>
</tbody>
</table>

6 FE modelling and analysis

For comparison with analytical methods, the sub-panels and T-section specimens were modelled and analysed using FE techniques. MSC PATRAN was used for
pre and post-processing; ABAQUS/Standard was the analysis software used. The actual development of FE modelling and analysis techniques, suitable for the types of structure investigated, was not a specific aim of this project. Rather, advantage was taken of existing expertise in FE analysis of fuselage structures within the Aerospace Research Centre at QUB. Existing techniques, described by Lynch [2], were used simply as a tool by which basic models could be built and analysed. The accuracy of such FE models has already been demonstrated by Lynch [2].

In light of the above, basic decisions such as element type and mesh density were essentially predetermined. Optimisation studies were not performed for the particular specimens in this project, and discussion as to the pros and cons of the various options is not included. This also applies to the analysis procedures adopted. The purpose of this paper is simply to present the techniques used and the results of the FE analyses and to compare these with experimental findings. The accuracy of the FE results can be judged against the analytical predictions.

![Figure 4: Boundary conditions for sub-panel specimens](image)

QUAD 8 (S8R5) shell elements were used throughout. These are 8-noded quadrilateral elements with 5 integration levels through the thickness. Models were assumed to consist of areas of parent and HAZ material with uniform properties in the same manner as for the analytical analyses. The same HAZ widths were used and the pad-up in skin thickness under a stringer was modelled by applying an offset to the thickness of the elements in that area. To account for material plasticity, true stress and logarithmic plastic strain values had to be derived for the parent and HAZ materials. This was done with the aid of the σ-ε
Curves for these materials. These curves can be generated using the values in Table 3 along with the Ramberg-Osgood equations [3]. Each analysis was performed in two separate parts:

1. A bifurcation buckling analysis was performed on a "perfect" model. This returned an eigenvalue from which the initial buckling load (for a perfect specimen) and corresponding mode shape could be determined.

2. A non-linear buckling analysis was then performed on the model using the Rik’s arc-length method for solution [4]. The model was seeded with imperfections based on the previously determined mode shape. This allowed the complete buckling and post-buckling behaviour of the model to be determined, i.e. from onset of loading through to failure. The magnitude of imperfection used was 10% of the skin thickness. The results from this analysis were subsequently processed to obtain a load-displacement curve for the particular model.

Meshing had to suit the geometry of the pad-up, the HAZ width and edge-support bars, i.e. such that nodes were coincident with the edges of the various zones, as well as allowing reasonable performance during analysis, i.e. run time and accuracy of results. This was based on the work of Lynch. Top, bottom and sides of the sub-panel models were fixed in translation in the 1, 2 and 3 (x, y, z) directions as shown in Figure 4. This was to represent the edge conditions offered by the Cerrobend and side-support bars on the test specimens. The T-section models were constrained in the same manner but with free edges between the inner faces of the Cerrobend. Loading was applied via a displacement in the -ve y-direction at the top row of nodes as shown in Figure 4. This was to simulate the action of the platen of the test machine used in the project. The displacement used for a particular model was based on experimental data and was sufficient to take the analysis to failure. The accuracy and validity of the FE analyses was judged by the degree of correlation between FE output, i.e. load-displacement curves and deformed shape plots, and experimental results. This is discussed in the next section.

7 Results

The following figures display experimental P-δ curves, FE predicted P-δ curves and the theoretical load levels for each of the specimens. A theoretical linear elastic stiffness curve is also shown for each specimen. This was used as a guideline against which to gauge how uniformly the particular specimen was being loaded during testing.

For the blade sub-panel, ST3BF, the FE analysis has over-predicted the skin buckling and ultimate failure loads compared to the test specimen. The FE has also slightly over-predicted the elastic stiffness of the specimen. However, compared to the theoretical predictions, the FE analysis could be considered reasonably accurate. All theoretical predictions under-estimated the ultimate strength of the specimen.

For the lipped sub-panel, ST3LF, the FE analysis has followed the experimental curve quite closely up to approximately 11.6 tonf, but has under-estimated the ultimate strength by a large margin. The FE analysis has, again,
slightly over-predicted the elastic stiffness of the specimen. This is thought to have been due to the overlap in shell thickness at the skin-stringer intersection.

The experimental curve for each T-section is seen to exhibit lower elastic stiffness than its theoretical curve. This was thought to have been due to experimental error in displacement measurement and not to some physical defect in the specimens. However, despite this fact, the FE analysis has gravely underestimated the ultimate strength of the blade specimen, TBCLAS. Only the eigenvalue buckling load is close to the experimental value. The other theoretical predictions agree reasonably well with the FE analysis. The reasons for this anomaly are not understood at this time. On the other hand, if one compensates for the experimental error for the lipped specimen, TLCLAS, the FE analysis, while slightly over-predicting the ultimate strength, agrees quite well with the test curve. All theoretical predictions over-estimate the ultimate strength in this case.

8 Conclusion

When judging the success of the FE analyses, the level of idealisation and simplification used regarding the extent and condition of HAZ material in each specimen must be borne in mind. Furthermore, the rigorous boundary conditions applied to the FE models were quite likely not maintained in practice, and the imperfections used to seed the models did not correspond exactly to manufacturing imperfections. It is therefore concluded that, while the outcome of the FE analyses cannot be regarded as highly accurate at this stage, the results are, however, very encouraging. There is plenty of scope for future work in this area, e.g. other shell elements and solution types can be tried, the HAZ and its properties can be modelled more precisely. More precise modelling will require more accurate information regarding the specimens and this can only be obtained via suitable measurement and experimental work.

References

Figure 5: Results for blade sub-panel specimens, ST3BF

Figure 6: Results for lipped sub-panel specimens, ST3LF
Figure 7: Results for blade T-section specimen, TBCLAS

Figure 8: Results for lipped T-section specimen, TLCLAS