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Design Optimization and Experimental Investigation On The Performance of A Light Weight Aircraft Wing Strut Having A Spot-Welded End Fittings

Engr. Stephen Tambari[1], Engr. Ayodele Akinola Samuel[2],
Engr(Mrs) Gloria I.F Dan-Orawari[3]
[1,2,3]Department of Mechanical Engineering Ken Saro Wiwa Polytechnics, Bori
Rivers State, Nigeria
Corresponding Author: Engr. Stephen Tambari

Abstract: *The main focus of this work is to design, manufacture and test a light weight aircraft wing strut having a pot-welded end fittings. This was designed against a compressive load of 2.6KN and a maximum deflection of 5mm. The work also covers the study of the mechanical behavior of the spot-welded end fittings fixed to the strut. It also conveys a comparative analysis between the experimental results and the mathematical analysis for failure of the members during testing. The major problem addressed by this study is that; during flight, the struts are subjected to tensile forces due to lift (upward forces) which acts on the wings of the aircraft. And during landing, the struts experiences compressive forces. Therefore, in order to overcome this, an investigation on tensile and compressive test was done. The test was to check for strength and shear of the weld and how much resistance they can offer before buckling. The results from the investigation and performance analysis showed that, the strut did not pass the test since its maximum deflection exceeded the 5mm set as the design criteria for the work and a further investigation was recommended. However, the design was successful in terms of the fittings test and also to overcome a compressive force of 2.6KN design criteria.*

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I. Introduction

Struts are structural members created to support the wings of aircraft in order to offer resistance to compressive forces acting on the wing. Struts are also used as chassis for motor vehicles to resist compression and to add strength to the design. Therefore, in a nutshell, this study works towards achieving the following

Objectives:

- To design, manufacture and test the strut using a fixed-fixed end condition.
- To find out the allowable maximum compressive load it can withstand before failure
- To determine the performance of the welds and the end fittings
- To compare the analytical (theoretical) stress with the material yield stress
- To compare the deflection with the design criteria
- To compare the theoretical shear stresses on the weld and plate with that of the experimental results
- To find out the mechanical or tensile behavior of the spot-welded joints.
- To compare all group test coupon data for the maximum forces and the number of welds
- To achieve an optimal design and make a viable design recommendation to be used as a basis for the light weight aircraft wing strut.

II. Methodology

Both experimental and analytical methods were used in this study.

Experiment 1:
Experimental procedure for the spot-welded end fittings;

- The surfaces of the plates were first cleaned with energy paper to remove rust and spots on the surfaces.
- The plate were then match marked to the required dimensions using scribers, square and metal rule.
- The points to be spot welded were then marked and aligned such that the full load will be transmitted through the welds to the plate.

- The Aluminum and steel were spot-welded noting the clearance and the center line on spot-welded machines. The welds were equally spaced to allow for uniform distribution of and to provide additional strength to the joints.
- Figure 1.0 shows the spot-welded end fittings setup before testing
- Figure 2.0 shows the spot-welded end fittings after testing.

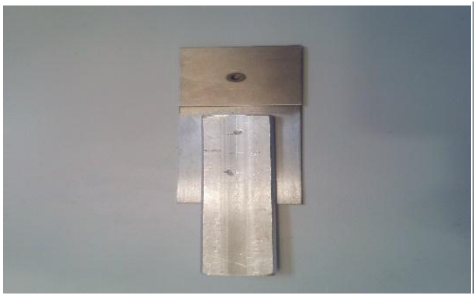



Figure 1.0 fitting before testing **Figure 2.0** fitting after testing

Experimental procedure for the tensile test of the plates and the spot-welded end fittings.
In order to test the plates and spot-welded end fittings, the following procedure were undertaken:

- The spot welded plates were properly clamped at both ends and centralized (as shown in Figure) to avoid operator's error
- The tensometer was connected to a computer to plot the behavior.
- The glass door of the tensometer was closed to protect against any injury in the event of any accident.
- The plates were then subjected to tensile loads at a gradual rate until it failed.
- The Mechanical behavior were plotted on the screen of the computer and the Fmax, Flim, Dmax and K values were recorded.
- The rate of shear failure were observed and photographed as shown in Figure
- The values obtained are shown in the result section

Statistical analysis for selecting the mean values from the group data.
From the coupon test data of various groups; the mean, the variance and the standard deviation was calculated and a 95% confidence interval was used to filter the normal data from the larger and smaller data. The final average acceptable data were obtained as shown in the result section

The two main sources of errors are;

- Wrong loading position
- Wrong clamping of the strut in the test rig

Experimental procedure for the Design, Manufacture and testing of the strut.

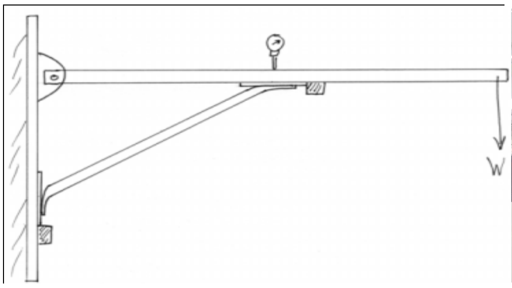


Figure 3.0 strut (schematic) in test rig [1] **Figure 4.0** strut during test

Procedure

- First the aluminum tube was cut to a length of 500mm
- Then 50mm was marked out at both end of the tube
- The two ends were then pressed to flatten in the materials lab
- The bending machine was then used to bend it to fit into the test rig
- The fitting were then clamped to the ends of the strut and spot-welded in the LEA laboratory

- Thereafter, the assembled parts were then taken to the material lab for testing
- The light weight strut was held firmly in the test rig and tested for several loads at different displacements until buckling occurred

III. Results Obtained

Results obtained for the end fittings

Table 1.0 Results obtained for Aluminium-Steel fitting test

Aluminium-Steel			
95% Confidence interval	Max. Values	Mean Values	Min. Values
Fmax, N	5394.38	3848.65	2302.92
Flim, N	5100.99	3446.79	1792.59
Dmax, mm	3.91	2.36	0.81
K, N/mm	3328.29	2472.34	1616.39

Table 2.0 Results obtained for Steel-Steel fitting test

Steel-Steel			
95% Confidence interval	Max. Values	Mean Values	Min. Values
Fmax, N	11087.22	10406.60	9725.99
Flim, N	9419.93	6839.32	4258.71
Dmax, mm	15.60	10.58	5.55
K, N/mm	4168.16	3287.52	2406.88

Results obtained for the Strut test

Table 3.0 Results obtained for Aluminium-Steel fitting test

Aluminium-Steel			
95% Confidence interval	Max. Values	Mean Values	Min. Values
Fmax, N	4364.66	3274.63	2184.59
Dmax, mm	8.91	6.11	3.32

Table 4.0 Results obtained for Steel-Steel tube fitting test

Steel-Steel			
95% Confidence interval	Max. Values	Mean Values	Min. Values
Fmax, N	3072.09	3072.09	3072.09
Dmax, mm	5.7	5.7	5.7

ASSUMPTIONS MADE FOR STRUT DESIGN

- The strut was assumed to be initially straight with uniform lateral dimension. This is because, imperfection may cause it to be out-of-straightness. But according to Euler's theory, no strut can be perfectly straight. Therefore, to enable proper measurement of the deflection from the center it was assumed straight. Finally, struts are compression members and are loaded in the direction of their length.
- The beam was also assumed to be eccentrically loaded. This is because, it is impossible to load the beam at the exact center of the strut. Also, due to the fact that bending moment is induced at every cross section by the load.
- It was assumed that, there are no locked-in stresses (residual stresses) in the strut. This assumption was made based on the fact that, differential heating and cooling normally arise during the rolling and forming processes and as result causing residual stresses.
- The strut was assumed to behave elastically up to failure. This because, at values not up to the buckling load the strut is bound to be in stable equilibrium which means deflection will be recovered. But at the buckling load, the strut is bound to be in a neutral equilibrium state and thus, deflecting theoretically.
- The weight of the strut is assumed to be negligible. This was done to achieve a light weight design and weight is not needed for aircraft design.

Boundary Conditions for the strut design

The Fixed-Fixed end joint was selected in order to minimize weight. So for Fixed-Fixed end conditions, the following boundary conditions exist:

- The effective length $L_{eff} = 0.5L$ where, L= Length
- There is no translational movement at the two ends in all directions (x, y, and z) of the strut.
- There is no rotational movement at the two ends in all directions (x, y, and z) of the strut.

Weld And Plate Shearing Analysis:

EXPERIMENTAL FAILURE ANALYSIS
CASE 1: ALUMINIUM-STEEL

- Shear failure of weld, $\tau_w = P/(\pi d^2/4) = 306.23$ Mpa where weld diameter, d = 4mm and P= F_{max}=3848.65N
- Shear failure of the plate, $\tau_p = F_{max}/(2(a-d/2)t) = 267.27$Mpa where a = 2d = 8mm and plate thickness, t = 1.2mm(18 gauge)

CASE 2: STEEL – STEEL

- Shear failure of weld, $\tau_w = P/(\pi d^2/4) = 827.98$ Mpa
  Where, P = F_{max}=10406.60N
- Shear failure of the plate, $\tau_p = F_{max}/(2(a-d/2)t) = 1084.021$Mpa where a = 6mm(1.5d) and plate thickness, t = 1.2mm

THEORETICAL FAILURE ANALYSIS
In this case, P = 2.6 x 10^3 Cos 40^0 and factor of safety (F.O.S) for aircraft design is 1.5 [2]
CASE 1: ALUMINIUM-STEEL

- The shear failure of the weld is given as: $\tau_{w1} = P/(\pi d^2/4) = 158.48$ Mpa
  With Factor of safety (1.5) [2], $\tau_{w1} = 105.65$Mpa
  The number of welds is = $\tau_w/\tau_{w1} = 2.89 \approx 3.00$ welds
- The shear failure of the plate, $\tau_{p1} = P/(2(a-d/2)t) = 138.31$Mpa
  With Factor of Safety (1.5) [2], $\tau_{p1} = 92.21$ Mpa

THE ANALYTICAL METHOD
STRUT DESIGN (BUCKLING) ANALYSIS
In this study, two methods (Euler's method and Perry Robertson's method) will be used to investigate the optimal design parameters and one among the two methods will be adopted based on the design criteria.

DESIGN CRITERIA

- The design should be capable of withstanding a compressive load of 2.6KN
- The design deflection should not exceed 5mm without failure
- The design should be light weighted
- The design should be easy to manufacture
- The design should fail due to buckling before failing due to shear of weld/plate
- The number of welded joints should be minimized

CASE1: ALUMINIUM-STEEL (FIXED –FIXED)
Using Euler's method
The critical load, $P_{cr} = \pi^2 EI/L_{eff}^{\wedge 2} = 17.49$KN Where, I = 1593.4$mm^4$, slenderness ratio, $\lambda = 48.32$ and A= 59.53mm^2, the material yield stress, $\sigma_y = 172$Mpa
The safe critical load (with factor of safety of 1.5) [2] = 11.66KN
The Euler stress, $\sigma_e = P_{cr}/A = 293.84$Mpa
It can be seen that, the Euler stress, $\sigma_e > \sigma_y$ material yield stress. It therefore, means that Euler method cannot be used. Secondly, according to [1] when the slenderness ratio is less than 140, Euler method overestimates the results. Therefore, Perry Robertson method is adopted in this report for the buckling analysis for strut design.

Using Perry Robertson method
The maximum stress,

$$\sigma_{max} = \frac{\sigma_y + \sigma_e(1+\eta)}{2} - SQR\left(\left(\frac{\sigma_y + \sigma_e(1+\eta)}{2}\right)^2 - \sigma_y \sigma_e\right)$$

$\sigma_{max} = 116.72$Mpa. Where, $\eta = 0.2855$

Therefore, $P_{cr} = \sigma_{max}$ x A = 6.948 KN
With factor of safety (1.5) [2], $\mathbf{P_{cr} = 4.63KN}$
But the experimental value for Aluminium-Steel, **Fmax = 3.27KN**

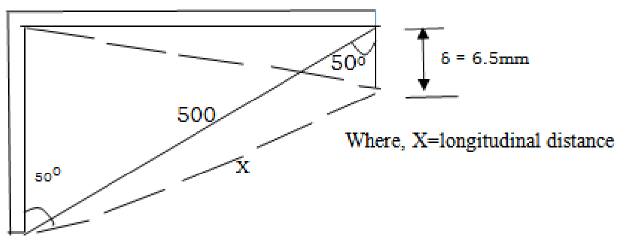
CASE 2: STEEL-STEEL (PINNED-PINNED)
Using Euler's method
$P_{cr} = \pi^2 EI/L_{eff}^{\wedge 2} = 4.373KN$
With factor of safety (1.5) [2], $\mathbf{P_{cr} = 2.92KN}$ where the slenderness ratio, $\lambda = 96.64$ and $L_{eff} = L = 500mm$,
Euler's stress, $\sigma_e = P_{cr}/A = 73.459Mpa$

Using Perry Robertson method

$$\sigma_{max} = \frac{\sigma_y + \sigma_e(1+\eta)}{2} - SQR\left(\left(\frac{\sigma_y + \sigma_e(1+\eta)}{2}\right)^2 - \sigma_y\,\sigma_e\right)$$

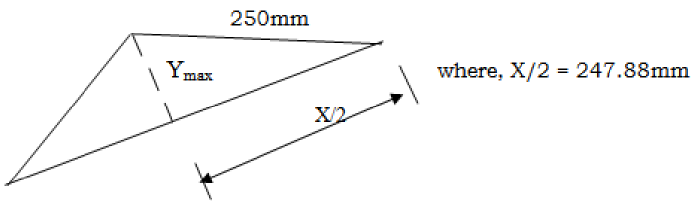
$\sigma_{max} = 61.582Mpa$
And $P_{cr} = \sigma_{max}$ x A = 3.67KN
With factor of safety (1.5) [2], $\mathbf{P_{cr} = 2.44KN}$
But the experimental value for Steel-Steel, **Fmax = 3.07KN**

THE MAXIMUM TRANSVERSE DEFLECTION ANALYSIS



Therefore, using Cosine rule to get X;

$$X^2 = 500^2 - \delta^2 - 2 \times 500 \times \delta \cos 50^o$$
$$X = 495.76mm$$



Therefore, Using Pythagoras theorem, $Y^2_{max} = 250^2 - (X/2)$ ^2
$Y_{max} = 32.72mm$
That means, @ a load, $F_{max} = 3.51KN$, the maximum deflection, $Y_{max} = 32.72mm$
Therefore, 2.6KN will give; (2.6 x 32.72)/3.51 = 24.24mm deflection which is more than the 5mm design criteria. The design therefore, did not meet the design criteria.

Table 5.0 Group data showing maximum transverse deflection and number of welds

Groups	F_{max}(N)	D_{max} (mm)	Maximum transverse Deflection(mm)	Transverse deflection @ 2.6KN(mm)	No of welds
1	3411.59	7.5	34.91	26.62	2
2	1257.09	5.5	29.86	61.62	4
3	3354.14	5.9	30.92	23.99	4
4	4403.49	7.5	34.91	20.63	3
6	3235.48	6.8	33.24	26.67	3
7	1699.50	4.5	26.98	31.75	3
8	3968.00	6.5	32.72	21.43	4
9	1315	4.5	26.98	53.14	3
12	1855.29	5.5	29.86	41.74	3
13	3733.68	5.0	28.41	19.80	4
14	3510.18	6.5	32.72	24.24	3
15	600	5.5	34.91	151.28	4
16	3659	7.5	34.91	24.79	4
18	1685.30	8.3	36.78	56.58	3
20	3281.25	5.0	28.41	22.52	3
21	3313.70	8.0	36.09	28.35	2
22	2583.50	3.3	23.11	23.29	3

IV. Discussion

Comparing the experimental results with the analytical results for fittings, it can be seen that the experimental values for Aluminium is far higher than that of steel and the theoretical values. This implies that, the fittings failed safe with adequate number of welds to improve the strength of the joint. It also means that, the stresses were evenly distributed and the overlap was very ok. Thus, making the fitting design meet the design criteria. Aluminium are good absorbers of shear stresses and can withstand compressive forces than steel.

During the buckling test of the strut, it was observed that, the strut did not buckle at the middle. This could be as a result of wrong loading position (not along central axis) or due to residual stresses.

Looking at the two methods used for the bucking analysis, the Perry Robertson's method was adopted for this work. This was done following the fact that, the slenderness ratio was less than 140 and the Euler stress for Aluminium was far greater than the material yield stress. Thus, making the Euler method invalid and not suitable as it will overestimate the results.

From the buckling test results, it can be seen that the critical load is far higher than 2.6KN which means that it failed safe.

The results from Aluminium showed that; experimental force = 3.27KN and Perry Robertson's critical load = 4.63KN. The theoretical value is greater than the experimental value due to assumptions made in the theoretical. But in the case of Steel, the experimental value = 3.07KN is less than Perry Robertson's critical load = 2.44KN. Which makes the Steel not to be a better choice.

From the group test data analysis, it can be seen that none of the group passed the third design criteria of not exceeding 5mm transverse deflection which may be due to wrong loading position. However, nearly all the groups passed the first and second design criteria of the fitting test and overcoming the compressive load of 2.6KN except group 22 that failed.

Optimal Design

- Aluminium on Steel fittings are better than Steel on Steel fittings for the design of aircraft strut. This is due to the fact that, Aluminium is a brittle material, non-corrosive and stiffer than Steel and therefore, can withstand compressive forces and shear stresses. It is also preferred for light weight design since it is lighter than steel.
- Steel sleeve is a bad choice as it add more weight to the design and causes the strut to deflect instead of buckling. Stresses are generated around the edges and thus, causes early failure.
- The overlap length should be increased in order to improve the tensile-shear strength of the spot-welded fittings by 3%.
- Increase in the number of welds gives better strength with lower transverse deflection. Therefore, number of welds should be increased and equally spaced to improve strength and equal stress distribution.

V. Conclusion

The Strut design did not pass the last design criteria of not exceeding a maximum deflection of 5mm. However, the design was successful in terms of the fittings test and also to overcome a compressive force of 2.6KN. In the overall, the strut did not pass all design criteria and therefore, was not successful. At this point, a further investigation or work should be done for a successful design that will give a maximum deflection less than the 5mm design criteria .

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