BUCKLING BEHAVIOR OF STRINGER STIFFENED CURVED PANELS MADE OF MAGNESIUM, ALUMINUM AND COMPOSITES UNDER COMPRESSIVE LOAD

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Abstract

During the last decade weight saving in commercial aircraft structures has become one of the important aspects of new aircraft design. In modern, commercial aircraft the structural weight constitutes about 40% of the total weight. Another 40% is fuel and 20% is the payload. Thus, it is obvious that the structural weight reduction should improve the fuel efficiency (by reducing fuel consumption) and reduce the emissions of a future aircraft.
The classical design of aircraft structures is based on Aluminum Alloys.
Lately, the main commercial aircraft designers and producers utilize more and more composite materials as a structural material.
The current design of the Boeing 787 Dreamliner and Airbus 380 utilizes high percentage of composite materials.
Magnesium Alloys were used in the fifties and the sixties as a structural material (B36) and disappeared as a result of corrosion problems.
Lately, the use of magnesium alloys was reconsidered due to the considerable improvement in surface protection solutions and appearance of high quality alloys.
When the reduction of structural weight is discussed, the use of new light materials has to be considered and the aspects of strength, manufacturability and cost should be examined.
Current applications show already very high costs in utilization of composite materials (high investment costs in the equipment and high production costs).
On the other hand, magnesium alloys use almost the same manufacturing technologies as aluminum and have almost the same electromagnetic properties.
The research and experimental work reported in this paper was done within the frame of FP6 European Community project AEROMAG, which dealt with Aeronautical Application of Wrought Magnesium. One of the goals of this project has been the validation of Magnesium as a structural material for aerospace components and structures.

1 Introduction

Analysis and testing of aircraft cylindrical panels made of magnesium alloys under compressive loading was one of the objectives of AEROMAG FP7 European project which dealt with validation of Magnesium as a structural material for aerospace applications.
For the above purpose several cylindrical panels made of magnesium alloys were constructed by using different joining technologies.
The current paper describes part of the experiment and analytical work that was performed at the Faculty of Aerospace Engineering, Technion, Israel Institute of Technology.
The panels consist of cylindrical skins and longitudinal stringers joined by two different welding techniques TIG (Tungsten Inert Gas) and LBW (Laser Beam Welding).
The TIG was performed at AMTS, Israel and LBM at EADS, Ottobrunn, Germany. The axial geometry is shown in the following paragraphs.

In the future investigations, panels with stringers joined by adhesive bounding and hybrid panels (magnesium skin +aluminum stringers) will be tested.
The analysis of a flat cylindrical panel reinforced by five longitudinal stringers under compressive loading was performed.
The problem of buckling was investigated on the basis of finite-element model with the help of NASTRAN Code.
In addition, critical loading was estimated by an approximate engineering method using reduction of the panel to a smooth, equivalent thickness, supported shell by smearing the areas of stringers, on the skin of the panel.
All analytical results were compared to the tests and to carbon composite panels of the similar dimensions.
On the basis of this comparison, recommendations for the structural improvement were given.

2 Initial Data

Geometry of the structure (Fig.2.1-2.3).
L-height of a panel, $L = 0.624m$,
t-thickness of the skin, $t_s = 2mm$
R-radius of curvature of the panel, $R = 937mm$
Length of an arch of the panel $S_0 = R\theta_0 = 0.68m$,
Arch distance between adjacent stringers $s = 136mm$.

Other sizes shown in table 2.1 and Fig. (2.1-2.3)
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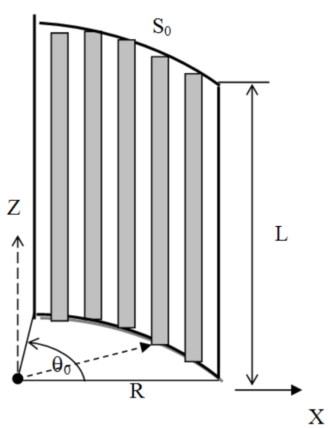

Fig. 2.1 Scheme of the Supported Panel

Table 2.1 The geometry sizes of two types of stringers (Fig. 2.2, 2.3).

	t_{str} [mm]	t_2	t_3	X_1	X_2	X_3	Y_1
Stringer laser welded	2.1	2	1	10	4.3	8	21
Stringer TIG welded	2.2	-	1.5	10	-	14	20.5

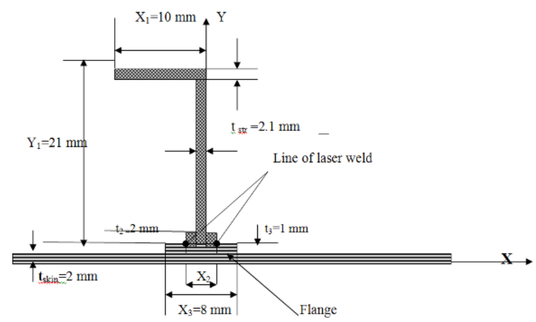

Fig.2.2 The sizes and attachment of a stringer by Laser welding.

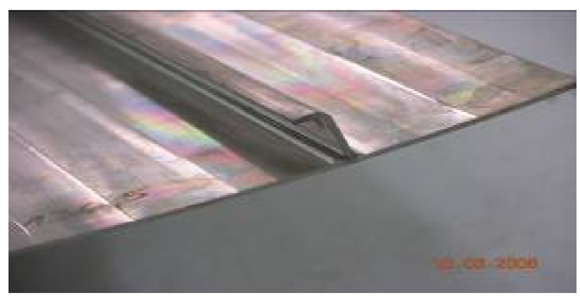

Fig.2.3 Stringer joined by LBW welding.

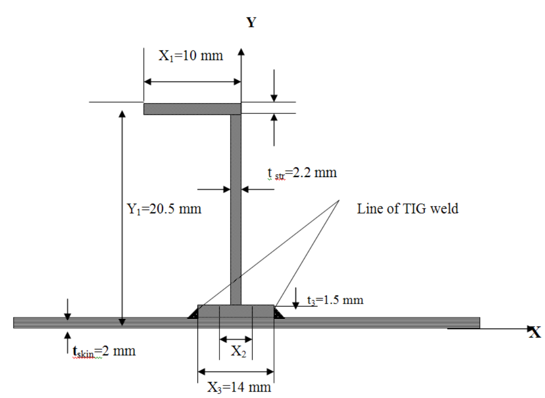

Fig.2.4 The sizes and attachment of a stringer by TIG welding.

Fig.2.5 Stringer joined by TIG welding.

Table 2.2 Stringers Area and Moment of Inertia.

	Area Stringer [mm^2]	Moment of Inertia Stringer Jx [mm^4]	Moment of Inertia Stringer Jy [mm^4]	Area of Cross Section of Panel A tot [mm^2]
Stringer by Laser welding	65.0	4.434	461	1736.0
Stringer by TIG welding	80.8	5.596	975	1811.7

Material Properties

Table 2.3 Material properties

Material name	Young's Modulus E [GPa]	Poisson's Ratio ν	Density ρ [kg/m^3]	σ_{ult} [MPa]
AZ31	45	0.35	1770	275
AL 2024-T3	70	0.33	2780	483
Carbon composite	59.5*	-	1640	600

*/ Look below

Assumptions: Magnesium and Aluminum Alloys isotropic materials.

Carbon: laminated composite material

Skin has symmetric of 2*8=16 layers

Skin has symmetric of 2*8=16 layers

$sym[90°/45°/-45°/0°/0°/-45°/45°/90°]$

Flange has symmetric of 2*12=24 layers

$sym[90°/45°/-45°/0°/0°/-45°/45°/90°/90°]$

Stringer has symmetric 2*9=18 layers

$sym[90°/45°/-45°/0°/0°/-45°/45°/90°/90°]$

Each layer has thickness $0.125mm$ and material orthotropic with properties.

For stringers middle layer has thickness $0.05mm$.

$E_{11} = 147.3\ GPa,\ E_{22} = 11.8 Gpa,$

Shear Modulus $G_{12} = 6GPa$.

E_{11} average defined by NASTRAN Code from numerical experiment. We gave vertical moving on $-1mm$ looked reaction and a pressure in vertical direction z.

Strain $\varepsilon_z = dl / L = -1/600 = -0.00167$

$$\text{Stresss}_z = \text{sum } (\text{reaction } p_z) / A$$

$$= -1.722 \cdot 10^5 / \ (1.736 \cdot 10^{-3}) = -9.92 \cdot 10^7 \text{ Pa}$$

$$E_{zz} = s_z / \ \varepsilon_z = 5.95 \cdot 10^{10} Pa = 59.5\ GPa$$

So, value $E_{zz\ average} = 59.5\ GPa$ for carbon (see Table 2.3).

Boundary Conditions

In analysis, the boundary conditions correspond to these obtained in a real experiment of the panel compression.

On lateral edges of the panel limit radial displacement and angel of rotation are as follows:

-In cylindrical system coordinate (r, θ, z) displacements

$$u_r = u_{,\theta} = 0 \qquad (2.1)$$

-At the top end edge of the panel conditions are realized

$$u_r = u_\theta = u,_r = u,_\theta = u,_z \qquad (2.2)$$

-Accordingly at the bottom end edge - conditions are clamp

$$u_r = u_\theta = u_z = u,_r = u,_\theta = u,_z \qquad (2.3)$$

3 Buckling Analysis of the Supported Cylindrical Panel

The problem of stability of the panel was dealt in two ways:
In simplified engineering, by converting data of a classical problem of stability of the closed supported shell to the smooth panel. Experience shows, that frequently simple engineering formulas give sufficient approach practice of 5-10 %. Also allow to estimate safety factor of a structure easily and quickly.
However in each concrete case, it is necessary to have more exact solution for an estimation of an error of the approximate approach.
In this case, a specified statement on the base of a finite elements method with the accurate account of geometry of a panel structure, stringers and boundary conditions (by Nastran Code) was needed.

3.1 Engineering Method to reduce a supported panel to isotropic panel by the smeared area of stringers.

Examining the engineering formula for calculation of critical loading of the supported panel, the advantage of the formula "smearing" the areas of cross-section of the stringers with no account for their moments of inertia i.e. F_{cr1}^{Panel} was used. The calculation was conducted using the formula (3.1)-(3.2), while the thickness t_{skin} in (3.1) was taken from the following formula:

$$t_{pan} = t_{skin} + A_{str} / l \qquad (3.1)$$

$$P_{cr1}^{smeared} = S\frac{Et_{pan}^2}{R\sqrt{3\left(1-\nu^2\right)}} = 0.616 \cdot SEt_{pan}^2 \qquad (3.2)$$

A – Area of cross section of stringer.
S – Length of arch of the Panel. S=0.68 m

Table 3.1 Force of buckling P_{cr1}. Analytical Solutions.

Type of stringer	A [mm^2]	$J_{x\ max}$ [mm^4]	t_{pan} [mm] smeared	Pcr1 analytical **[Ton]**
Supported Panel. Stringers laser welded	67.1	4434	2.49	**12.51**
Supported Panel Stringers TIG welded	80.8	4804	2.59	**13.54**

3.2 Buckling Analysis by Nastran Code

Panels were modeled by finite elements shell's types and properties of three types on thickness.

Table 3.2 Types of elements and sizes (see Fig.3.1)

Name of sizes	stringers type laser weld [mm]	stringers type TIG weld [mm]
t_{skin} (color white)	2	2
t_{str} (color aqua)	2.1	2.2
t_{flang} (color red)	3	3.5
h_{str} (color aqua)	22	21.5

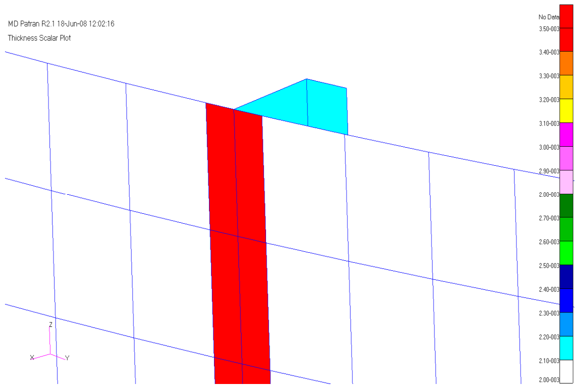

Fig. 3.1 Types of shell's elements categorized by thickness

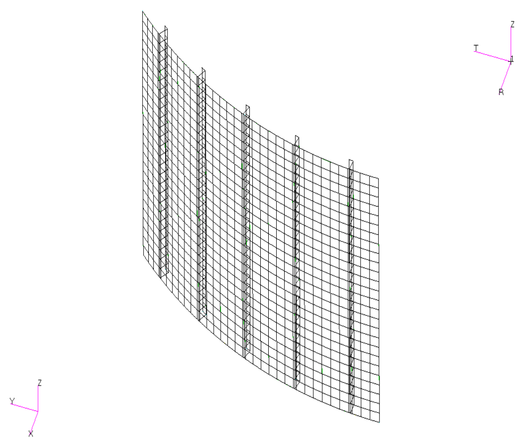

Fig. 3.2 General view of FE model for NASTRAN Code

Table 3.3 Comparison of Buckling Results and Strength for Supported Panels

Type of stringer	$P_{cr1\ Smeared}$ [Ton]	$P_{cr1\ Nastran}$ [Ton]
Supported panel. Stringers laser welded	**12.51**	**13.31**
Supported panel Stringers TIG welded	**13.54**	**14.65**

4. Test of Supported Panels under Compressive Load and Analysis of Results

For the estimation of the panel ability to withstand the compressive load, it is necessary to compare the loading of buckling with the loading in which the material will pass into a plastic irreversible condition.

Buckling is defined as a loading at which all surface of the panel becomes covered by dents in chessboard-like pattern.

During the test the laser-welded panel has buckled at $P_{cr1\ test} = 11.12 ton$, and then in places of dents there was a transition into a crash condition at $P_{crash} = 11.20 ton$. (Appendix 2).

For TIG-welded panel the test results were as follows:

- buckling condition $P_{cr1\ test} = 14.56 ton$,
- a crash condition $P_{crash} = 14.57 ton$.

Results of these tests show that the loading of buckling and the exhaustion of load-carrying ability are practically coinciding. Unloading of panels has shown that buckling creates an irreversible plastic deformation of panels i.e. load-carrying ability of panels is defined by their critical loading P_{cr1}.

Stability of the compressed panel is proportional to its rigidity E^* in a vertical direction. Let's examine experimental results of the rigidity of the panels under compressive loading.

In Fig 4.1, angle of a tangent line of loading- vs-shortening of the panel shows that the Young modulus of the panel with laser-welded stringers (30.4 Gpa) is lower than the modulus of TIG-welded stringers (41.6 Gpa). The corresponding ratio of critical loadings $P_{cr1} = 11.2 ton$ to $14.56 ton$ shows advantage of TIG over laser welding.

In order to estimate the sensitivity of panels made with two different structural stringers a numerical experiment by NASTRAN Code was made in which elements of welding has been changed by using the following modules of elasticity of the flange (red color finite elements of flange on Fig. 3.1):

-First variant $E_{flange} = 45 GPa$,

-Second variant $E_{flange} = 35GPa$.

Results of calculations of P_{cr1} and E_z^* are presented in the table 4.4.

Table 4.4 Sensitivity of panels structures to decrease in elasticity of stringer joint (flange) with a skin. Calculated by NASTRAN Code.

$E_{flange} = 35Gpa$ / $E_{flange} = 45Gpa$	**Stringers type of Laser weld** $E = 35Gpa$ / $E = 45Gpa$	**Stringers type of TIG weld** $E = 35Gpa$ / $E = 45Gpa$
P_{cr1}	10.6 / 13.31 -20.4%	14.0 / 14.65 -3.8%
E^*_z from Nastran Code	36.7 / 45.9 -20%	44.5 / 45.9 -3.0%

From the Table 4.4 it can be seen that the LBW structure is very sensitive to the change in E, where the TIG structure is not.

5. Conclusion

Summarizing the obtained results of calculations and tests of the panels under compressive loading the following conclusions can be drawn at this stage of the investigation: The ability to withstand compressive loads of Magnesium Alloy made panels with two kinds of longitudinal stringers, welded by TIG and LBW, is defined by critical buckling load P_{cr1}.

The experiments show that buckling occurs in elastic-plastic stage.

Buckling of the panel with LBW welded stringers occurs at 11.12 tons, while the TIG welded panel at 14.56 ton.

There are two principal reasons for this difference in the critical loading:

- The area cross section of the flange (defined at Table 2.2) in LBW welding is smaller than that of TIG welding ($65mm^2$ and $80.8mm^2$ correspondingly), therefore resists lower buckling load.

- The laser welding seams are closer to each other, than the TIG seams, therefore resist less bending moments, which appear due to inaccurate alignment of the stringer axis with regard to the panel axis.

a) Numerical experiment by Nastran Code examined the sensitivity of the critical load with regard to Young modulus (stiffness). The results of the examination for two type stringers were shown in Table 4.4 for $E = 35GPa$ and $E = 45GPa$.
   Correspondingly, the TIG type has been less sensitive (3.8%) than LBW (20.4%).

b) From Fig 4.1 it is possible to see the results of equivalent modulus E* of structure measured in experiment and obtained by Nastran Code. It can be concluded, that in the Laser case, the deviation from Nastran Code is much higher than for TIG.

   This is explained by worse alignment of LBW welded stringer than the TIG one.

   The misalignment was measured and it was found that the angle of deviation from the longitudinal axis of the panel has been about $1°$. In such a case, compressive load applied to the edge of the panel creates a bending moment on the stringer and therefore decreases its resistance to buckling and its rigidity (E^*). In order to draw final conclusion to this topic there is a need to investigate further the deviations in geometry of stringers with regard to the panel axis.

c) In order to compare the two technologies of welding fairly, the geometries must be exactly the same (the area cross sections) and the distances between the welding seems. In addition, the longitudinal alignment of stringer with regard to the panel axis should be measured prior to the test. The two types should be selected for the test with similar deviations.

From the point of view of the welding technology, the improvement must be obtained in the proper alignment of the stringers. It has, of course, influence on the proper design of jigs and fixtures.

It is recommended to continue, both experimental and analytical investigations of the panel stability for different combinations of skin, stringers and types of joining (TIG, LBW and adhesive bonding).

References

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Appendix 1: Analysis Buckling of the Supported Panel by NASTRAN Code

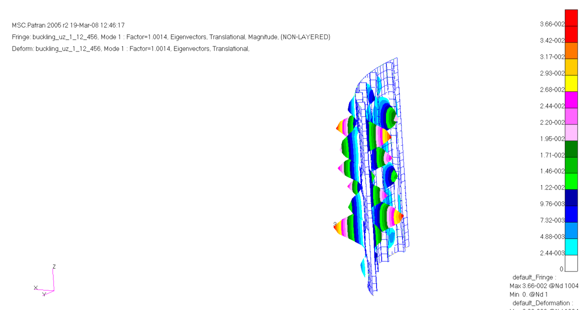

Fig. A1-1 Buckling of the Supported Panel. View in profile (laser weld of stringers).

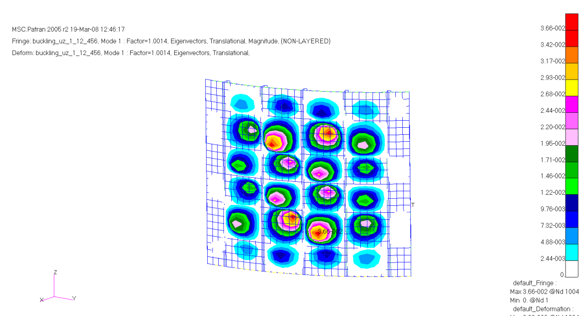

Fig. A1-2. Buckling of the Supported Panel. View in face (laser weld of stringers).

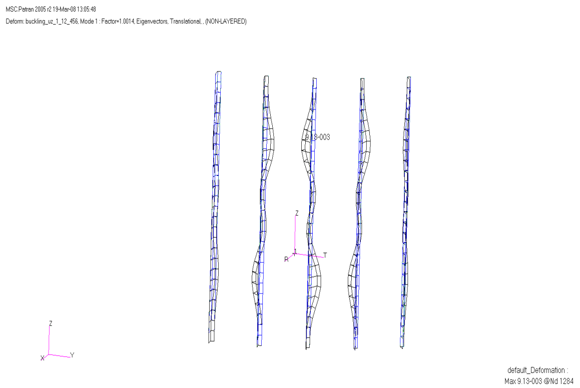

Fig. A1-3. Buckling of the Supported Panel. Deformation of stringers from plane.

Appendix 2: Tests Results of Supported Panel

Fig. A3-1. The panel is after buckling (Load P_{cr1}=10.6 Ton). On Picture Load 10.9 ton Laser weld.

Fig. A3-2. The panel is before plastic state (Load $P_{cplastic}$=11.2 Ton). On Picture Load 11.0 ton Laser weld.

Fig. A3-3 Residual plastic deformations after unloading the panel. Side external. Laser weld. Irreversible plastic deformations of a skin are visible.

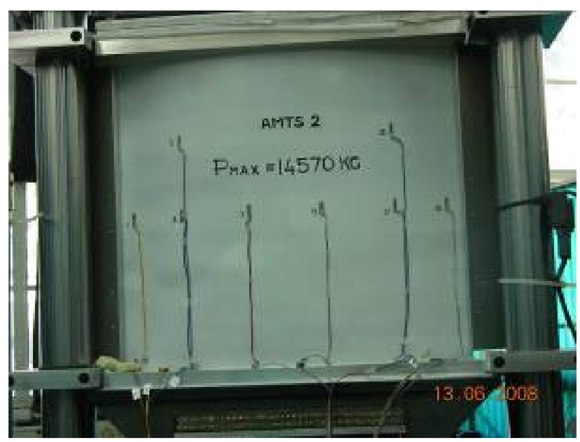

Fig. A2-5 Residual plastic deformations after unloading the panel. Side external. TIG Weld. Irreversible plastic deformations of a skin are visible