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Optimizing the Rubber Backed Bending Process

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<td>------------------------------------------------</td>
</tr>
<tr>
<td>Arall</td>
<td>ARamid ALuminium Laminate</td>
</tr>
<tr>
<td>Glare</td>
<td>GLass REinforced metal laminates</td>
</tr>
<tr>
<td>LT</td>
<td>Longitudinal/Transverse direction</td>
</tr>
<tr>
<td>L</td>
<td>Longitudinal direction</td>
</tr>
<tr>
<td>h</td>
<td>Height of rubber cushion</td>
</tr>
<tr>
<td>v</td>
<td>Displacement of the form tool</td>
</tr>
<tr>
<td>d</td>
<td>Cushion's hole diameter</td>
</tr>
<tr>
<td>r</td>
<td>Bend radius</td>
</tr>
<tr>
<td>F</td>
<td>Bending force</td>
</tr>
<tr>
<td>Al</td>
<td>Aluminium</td>
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</table>
SUMMARY

An ideal process to bend components of fibre metal laminates is rubber backed bending.
In this report it is shown that the formability of a rubber cushion is related to its hardness and its geometry. If the hardness of the rubber cushion is lower or the geometry more open (block with larger cavity) the force necessary to give a particular deformation will be smaller.
Also the force necessary to bend a particular sheet material depends on the bending stiffness of the material and the size of the used radius. If the bending stiffness increases or the bend radius increases the required force will increase too.
Finally the report gives a relation between the quality of a bend-line for a particular fibre metal laminate, the force required to bend the material and the rigidity or geometry of the used cushion. This relation is useful when bending such laminates so that defects due to excessive force or a wrong selection of cushion geometry or hardness may be avoided.
1. INTRODUCTION

There are various rubber forming processes which may be suitably applied to bend fibre metal laminates and aluminium alloys. Rubber forming is a name given to a family of forming processes which employ elastomeric or rubber tools to apply deformation forces to the sheet material. This report is particularly concerned with one of these processes better known as rubber backed bending.

In rubber backed bending although one rubber die can be used for many bend-lines with different flanges, bend radii, or material thicknesses, the used cushion will be an optimal die for a few configurations only.

During bending operations in the past it has been observed that one rubber cushion had different results for different material/geometry configurations, especially for fibre metal laminates. One could state that the efficiency of the cushion is related to the material, the material thickness and the radius to be bent. The same could be said for other bending processes, for example, in air bending the gap is related to the material and its thickness.

The variables which determine the efficiency of the cushion for a particular configuration are:
- the deformation necessary,
- the bending stiffness of the cross-section,
- the hardness of the rubber used, and
- the geometry of the cushion.

It is the purpose of this report to investigate and relate all these variables in order to be able to optimize the rubber backed bending process.
2. FIBRE METAL LAMINATES

2.1. Introduction

The development of new aircraft is strongly influenced by the introduction of new structural materials. The driving force behind such developments is the everlasting incentive of reducing aircraft operating cost. As can be seen in Figure 1 an increasing part of the operating costs will be spent on fuel and maintenance. It will be cost effective if aircraft structures can be designed of new materials to obtain a lower weight and to require less maintenance. Several materials may be considered for the future aircraft structure (excluding engines, landing gears, and other systems). There are three potential families: aluminium alloys (both conventional and new), composites, and fibre metal laminates.

![Diagram showing the relation between DOC and aircraft empty weight.]

Figure 1
The relation between DOC and aircraft empty weight.

2.2. What are fibre metal laminates?

Fibre metal laminates, commonly known as ARALL, were developed by the Delft University of Technology and consist of adhesive bonded laminates which combine the advantages of high strength isotropic metal sheets with the fracture resistance of aramid, glass, or carbon fibres. As can be seen in Figure 2 the material is built up as a laminated sheet with layers of high strength metal alloy sheets (e.g. aluminium or titanium) and layers of strong unidirectional or cross-ply fibres, impregnated with a thermoset or a thermoplastic adhesive. In this way a large family of structural materials was generated, creating an infinite variety of laminates for the designer. By choosing the right material and laminate build up, all mechanical properties like static strength, fatigue strength, stiffness, and fracture toughness can be tailored to any desired application. For example, a large range of different lay-ups are possible, from a 2/1 lay-up (two layers of metal alloy sheet bonded by one layer of prepreg) to any (uneven) number of layers.
Fibre metal laminates were thus developed to obtain a material with good fatigue strength in which cracks would propagate very slowly. Fatigue cracks grow in a direction perpendicular to the maximum principal stress. Therefore a high percentage of fibres should be oriented in the direction of the maximum principal stress. The function of the fibres is to resist crack opening as shown in Figure 3. The crack-bridging of the fibres produces an effective decrease or even a stop in the crack growth. In this way fibre metal laminates combine the favourable static properties of high strength metal alloys with good fatigue resistance of fibre reinforced materials.

![Figure 2](image)

**Figure 2**
Fibre metal laminate (3/2 lay-up).

![Figure 3](image)

**Figure 3**
Fatigue crack-bridging in ARALL laminate.

With all these advantages in mind, weight savings of about 25% are easily attainable. Furthermore, these laminates may be handled the same way as monolithic metals. The material can be cut, drilled, sawn, and milled by normal workshop procedures. Standard joining techniques like riveting, bolting, and bonding are also possible.
2.3. Possible applications of fibre metal laminates

Because of their good mechanical properties, fibre metal laminates can replace aluminium alloys in some major parts of the aircraft structure. Structures made of fibre metal laminates are structures for which fatigue and damage tolerance are important design criteria. Future applications might involve the following primary aircraft structures as related to Figure 4:

1. The fuselage;
   Fatigue is the primary load on the fuselage arising from the pressurisation of the inner cabin. Other loads include manoeuvre and gust loads.

2. The lower wing skin panels;
   These are subjected to manoeuvre and gust loads. Both these loads are superimposed by a tensile load. The upper wing panels are mainly loaded in compression for which competitive materials are available.

3. The horizontal stabilizer;
   Such a structure experiences the same load as experienced by the wing structure.

Figure 4
Primary aircraft structures in which ARALL may be used.
3. THE RUBBER BACKED BENDING PROCESS

3.1. Introduction

Rubber backed bending employs a rubber pad on the platen and a form tool on the ram. As the form is pressed onto the block the rubber acts as a flexible die exerting nearly equal pressure on the work piece surfaces in contact with the rubber. See Figure 5.

The major advantages of the rubber backed bending process are:

1. One rubber pad takes the place of many different die shapes, returning to its original shape when the pressure is released.
2. Tools have fewer components and are made of easier-to-machine materials than conventional tools.
3. No protection of the work piece surfaces is required since the rubber does not scratch the material as occurs in conventional bending.
4. Using this process a more even distribution of the deformation is obtained.

Some disadvantages of the rubber backed bending process are:

1. Rubber, which is expensive, wears out quickly, or tears on sharp edges. The average life of a rubber pad is about 20,000 cycles.
2. Without special or accessory equipment, rubber pads exert less pressure, and the product definition may be less sharp than with conventional dies.
3. Shrink flanges may have wrinkles that need hand work afterwards.
4. High friction between the material and the rubber pad which results in large shear stresses superimposed on the large tensile stresses due to bending. As a result premature failure of the material results. This friction is usually reduced using hollow rubber pads.

Figure 5
Tooling and setup for rubber backed bending.
3.2. When is rubber backed bending used?

Components of fibre metal laminates with curved flanges, made of unidirectional material, are suitable for rubber forming. Other features, like joggles, burdles, etc., can be formed as well. Rubber forming is an acceptable process for components in which the fibre direction is not too important since the fibre direction is related to the position of the component. Differences in fibre directions will result in different spring back angles and more complex tooling. Rubber forming seems to be suitable for unidirectional and cross-ply laminates with small thicknesses (e.g. 2/1, 3/2 and 4/3 lay-ups). Furthermore, rubber backed bending is a particular process for fabricating stringers as shown in Figure 6.

![Figure 6](image)

Z-stringer, 2/1 lay-up.

3.3. Equipment used

The main tools for the process are the 100mm long rubber pads and the forming tools. The four rubber pads used had a hardness of about 85 Shore A and it was made sure that the rubber cushions were at least three times deeper than the part to be formed. One pad consisted of a solid block, whilst the other pads had centred holes drilled through them of 15mm, 25mm, or 35mm diameter. The forming tools consisted of circular rods having various diameters. The retainer, or casing, which is usually made of steel or cast iron must be strong enough to withstand forming pressures of about 2000 - 10,000psi. Also the height - h (see figure 5) was varied to investigate its influence.

The sheet material used included aluminium alloys and fibre metal laminates. The aluminium alloys used were of the 2024-T3, 6061-T6, and 7075-T6 type. Each alloy type was obtained with the following thicknesses: 0.5mm, 1.0mm, 1.5mm, and 2.0mm. The fibre metal laminates used were Glare 2 and Glare 3. For both laminates 2/1, 3/2, and 4/3 lay-ups were used. For Glare 2 the aluminium alloy is 2024-T3 whilst the prepreg is a non-stretched, unidirectional, glass type. See Figure 7.
For Glare 3 the aluminium alloy is also 2024-T3 but the prepreg is a 50/50 cross-ply, non-stretched, glass type. See Figure 8. For the mechanical properties of both the aluminium alloys and the fibre metal laminates see Table 1.

![Figure 7](image_url)
Figure 7
Build up of Glare 2.

![Figure 8](image_url)
Figure 8
Build up of GLARE 3.

### Mechanical properties

<table>
<thead>
<tr>
<th></th>
<th>Glare 1(1)</th>
<th>Glare 2(2)</th>
<th>Glare 3(3)</th>
<th>Glare 4(4)</th>
<th>Aramid(5) Arali 1</th>
<th>Aramid(5) Arali 2</th>
<th>2024-T3</th>
<th>7075-T6</th>
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<tbody>
<tr>
<td>Tensile ultimate</td>
<td>L 1500</td>
<td>1250</td>
<td>755</td>
<td>1040</td>
<td>1300</td>
<td>1150</td>
<td>800</td>
<td>717</td>
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<tr>
<td>strength, MPa</td>
<td>LT 560</td>
<td>520</td>
<td>755</td>
<td>618</td>
<td>586</td>
<td>517</td>
<td>455</td>
<td>435</td>
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<td>Tensile yield</td>
<td>L 550</td>
<td>400</td>
<td>520</td>
<td>560</td>
<td>621</td>
<td>591</td>
<td>324</td>
<td>483</td>
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<tr>
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<td>LT 340</td>
<td>250</td>
<td>320</td>
<td>260</td>
<td>331</td>
<td>228</td>
<td>290</td>
<td>469</td>
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<tr>
<td>Elastic tensile</td>
<td>L 64.7</td>
<td>55.6</td>
<td>57.5</td>
<td>56.4</td>
<td>67.6</td>
<td>64.1</td>
<td>72.4</td>
<td>71.1</td>
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<tr>
<td>modulus, GPa</td>
<td>LT 48.2</td>
<td>50.2</td>
<td>57.5</td>
<td>50.3</td>
<td>48.5</td>
<td>49.0</td>
<td>72.4</td>
<td>71.1</td>
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<td>Ultimate strain %</td>
<td>L 4.6</td>
<td>5.1</td>
<td>5.1</td>
<td>1.9</td>
<td>7.7</td>
<td>12.7</td>
<td>13.6</td>
<td>8</td>
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<tr>
<td></td>
<td>LT 7.7</td>
<td>13.6</td>
<td>5.1</td>
<td>7.7</td>
<td>12.7</td>
<td>13.6</td>
<td>8</td>
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<tr>
<td>Bearing Ultimate</td>
<td>L 770</td>
<td>704</td>
<td>690</td>
<td>700</td>
<td>758</td>
<td>565</td>
<td>890</td>
<td>1056</td>
</tr>
<tr>
<td>strength, MPa</td>
<td>LT 704</td>
<td>690</td>
<td>700</td>
<td>758</td>
<td>565</td>
<td>890</td>
<td>1056</td>
<td></td>
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<tr>
<td>Blunt notch</td>
<td>L 805</td>
<td>775</td>
<td>501</td>
<td>605</td>
<td>495</td>
<td>405</td>
<td>420</td>
<td>550</td>
</tr>
<tr>
<td>strength (circular)</td>
<td>LT 560</td>
<td>290</td>
<td>501</td>
<td>420</td>
<td>386</td>
<td>311</td>
<td>420</td>
<td>550</td>
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<tr>
<td>Sharp notch</td>
<td>L 710</td>
<td>850</td>
<td>409</td>
<td>530</td>
<td>537</td>
<td>362</td>
<td>320</td>
<td>550</td>
</tr>
<tr>
<td>strength (jawcut)</td>
<td>LT 230</td>
<td>230</td>
<td>409</td>
<td>320</td>
<td>280</td>
<td>250</td>
<td>320</td>
<td>350</td>
</tr>
<tr>
<td>Density, g/cm³</td>
<td>2.52</td>
<td>2.52</td>
<td>2.52</td>
<td>2.45</td>
<td>2.35</td>
<td>2.35</td>
<td>2.78</td>
<td>2.78</td>
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</tbody>
</table>

(1) 5/2 lay-up: thickness is 1.4 mm (with 0.5 mm thick aluminium)
(2) 5/2 lay-up: thickness is 1.65 mm (with 0.5 mm thick aluminium)
(3) 5/2 lay-up: thickness is 1.3 mm (with 0.3 mm thick aluminium) data partly from Alcoa
(4) data partly from Mil. Handbook 5E

Table 1
3.4. Failures in rubber forming

Any blank may be transformed to the desired shape like flanges, etc., as long as the deformation is slight to moderate. If forming is severe, auxiliary tools must be used to support the work piece and prevent wrinkling. This is mostly evident with the laminates. Furthermore, shear stresses play an important role in the fabrication of small flanges (small flange height). When the flange becomes too small, edge delamination will occur due to the high shear stresses just outside the curved zone. Again this is mostly evident in fibre metal laminates. Figure 9 gives the principal types of failure in curved flanges of fibre metal laminates made by rubber-pad forming.

A perfect bend.

Fracture due to a small bend radius.

Wrinkling due to lack of support.

Delamination due to lack of support.

Edge delamination due to small flange height.

Figure 9
4. THE TEST PROCEDURE

4.1. Bending aluminium alloys

The test was carried out by first bending cheap material (aluminium) in order to acquire an idea of what variables influence the process most. The results obtained were later used for bending fibre metal laminates.

The aluminium alloy test specimens were cut to a dimension equal to 80mm by 60mm. The tests were carried out using a hydraulic press interfaced with a graphical recorder in which the Y-axis represented the bending force and the X-axis represented the displacement of the forming tool. The three types of alloys were each bent over a radius of 4mm, 6mm, and 8mm. For each radius the block geometry and the height of the block were varied.

For each set-up a Force versus Displacement \([F/v]\) graph was drawn on the graphical recorder. All the aluminium alloys were bent to a product angle of approximately 90°. In this way it was assured that the material was bent to an appropriate and comparable bend angle.

From the \(F/v\) diagrams obtained the initial gradient was calculated. Furthermore, it was deemed necessary to record the force at particular displacements. The displacements chosen were 5mm, 10mm, 15mm, and 20mm. Such procedure was required to select the most consistent results. See Figure 10.

\[
\text{SCALE:} \\
1\text{cm } \uparrow = 1000\text{kgF} \\
1\text{cm } \rightarrow = 0.5\text{cm displacement of form tool}
\]

- \(r = 8\text{mm}\)
- \(h = 20\text{mm}\)
- \(d = 25\text{mm}\)
- material is 2024-T3

initial gradient is 4000N/cm
force at \(v = 5\text{mm}\) is 2000N
force at \(v = 10\text{mm}\) is 4000N
force at \(v = 15\text{mm}\) is 5600N
force at \(v = 20\text{mm}\) is 7200N

Figure 10
A \(F/v\) curve for an alloy set-up showing the recorded results.
Due to its consistency the force at 15mm displacement [F] was chosen to plot graphs of F versus Yield Strength of the aluminium alloy, F versus Hole Diameter of the block, F versus Bend Radius, and F versus Height. See Graphs 1 to 8. As can be seen from these graphs the largest influence on the bending of the aluminium alloys was the block geometry and the height of the block. Hence such influence must also be evident for the laminates and these will be the main variables when bending such materials.

4.2. Bending fibre metal laminates

Glare 2 and Glare 3 specimens of 2/1, 3/2, and 4/3 lay-ups were then cut as shown in Figure 11, taking particular care for the material direction.

![Bend-Line](a) LT direction, (b) L direction.

After being cut some special attention was given to the finish of the specimen edges. A rough edge can easily cause tearing or cracking of the outer aluminium layer at that edge. Hence particular care was taken by grinding all edges prior to bending. Again F/v curves were obtained this time by bending (both in the LT and L directions) the laminates to their minimum bend radii plus allowing a 1mm factor of safety. The minimum bend radii of the laminates are given in Table 2. For each set-up the block geometry and the height of the block were varied.

<table>
<thead>
<tr>
<th>Material</th>
<th>Lay-up</th>
<th>NBR (L)</th>
<th>NBR (LT)</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Alu/Comp</td>
<td>Measuring</td>
<td>Measuring</td>
<td>Measuring</td>
</tr>
<tr>
<td>Glare 2</td>
<td>2/1</td>
<td>1.00</td>
<td>2.00</td>
<td>0.78</td>
</tr>
<tr>
<td>Glare 2</td>
<td>3/2</td>
<td>11.0</td>
<td>3.50</td>
<td>1.46</td>
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<tr>
<td>Glare 3</td>
<td>4/3</td>
<td>&gt;12</td>
<td>6.50</td>
<td>2.00</td>
</tr>
<tr>
<td>Glare 3</td>
<td>2/1</td>
<td>2.25</td>
<td>2.50</td>
<td>0.87</td>
</tr>
<tr>
<td>Glare 3</td>
<td>3/2</td>
<td>7.00</td>
<td>5.00</td>
<td>1.48</td>
</tr>
<tr>
<td>Glare 3</td>
<td>4/3</td>
<td>&gt;12</td>
<td>13.00</td>
<td>1.95</td>
</tr>
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</table>

Table 2
Minimum bend radii of Glare laminates.
As with the case of the aluminium alloys the initial gradient of the F/v curves was recorded, so was the force at particular displacements (5mm, 10mm, 15mm and 20mm). See Figure 12. Graphs of F versus Height, F versus Hole Diameter, and F versus Yield Strength of the laminates were again plotted. See Graphs 9 to 18. From Graphs 17 and 18 it is evident that the yield strength has practically no effect on the bending of the material as compared to the block geometry and the height. Graphs 9 to 18 give a clear indication of any product failures too. The filled markers indicate such failures.

**SCALE:**

1cm ↑ = 1000kgF  
1cm → = 0.5cm displacement

- r = 3mm  
- h = 40mm  
- d = 25mm  
- material is Glares 2  
  (2/1 lay-up, LT)  
  
  initial gradient is 3700N/cm  
  force at v = 5mm is 1400N  
  force at v = 10mm is 2200N  
  force at v = 15mm is 2800N  
  force at v = 20mm is 3200N

**Figure 12**

A F/v curve for a laminate set-up showing the recorded results.
5. DISCUSSION OF RESULTS

5.1. Inspecting the behaviour of the aluminium alloys on bending

During the course of the experiment, whilst obtaining F/v diagrams for the aluminium alloys, it was observed that in some cases the block's cavity was not large enough and during the bending process the entire cavity was closed. When full closure of the cushion cavity occurred the force increased considerably for a small displacement. At this stage the cushion acts as a solid one. With the laminates, however, no sufficient force was reached as to close a cavity completely. If such forces were achieved the material would have already failed.

As already pointed out the greatest influence on the bending force is the block geometry, see Graph 1. As expected the radius to be bent also influences the force, that is, the bigger the radius the bigger the force. Graph 1 illustrates that this is only so for a solid block. Graphs 2 to 4 corroborate these conclusions too. They show that the force is largest when the height is smallest and that for large radii the difference in force as the height increases is more significant for the stiffer blocks.

On the other hand Graph 5 shows that the yield strength of the aluminium alloy does not influence the force very significantly.

5.2. Inspecting the behaviour of the fibre metal laminates on bending

From the F/d curves (graphs 9 to 12) it is evident that bad products (shown in Figure 13) are most likely to be obtained when the hole diameter is less or equal to 15mm. As d increases a transition value is reached beyond which all products are good. When considering Glare 2 in the 4/3 lay-up - Graph 10 - this transition point is somewhat uncertain. The first and third markers are filled indicating that the second marker could have easily been filled too. This however should not be taken as a general rule since the defect that occurred in the third specimen is fracture and had the bend radius been slightly increased such a defect would have been avoided.

Graphs 9 to 12 are also evidence to the fact that the force necessary to bend a particular material must increase if the block geometry (d in this case) decreases. The hardness of the rubber was kept constant throughout. Another observation from these four graphs is that for a particular hole diameter a larger force is required to deform 4/3 lay-ups, whilst a smaller force is required to deform 2/1 lay-ups. This is due to the different thicknesses of the laminates used.
Another set of useful graphs are Graphs 13 to 16. Again as the height increases from 10mm to 40mm a transition value is passed where all products are likely to be good. This is mostly evident with Glare 3 for lay-ups of 3/2 and larger (see Graphs 15 and 16). For smaller lay-ups the force is less and little defects are evident. See Figure 13. The transition region occurs also for Glare 2 in the L direction but for Glare 2 in the LT direction all products seemed to be good. Glare 2 with a 4/3 lay-up (Graph 14), as already mentioned, fractured but this could have easily been avoided by increasing the bend radius.

The height, which too determines the hardness of the rubber, influences the force applied to deform the material in such a way that a smaller height implies a larger force. Zero height was not considered due to the high probability of defects.

From Graphs 13 to 16 it is also evident that the force required to deform the material when \( h = 10 \) and 40 is larger in the L direction than in the LT direction. The rate of decline of the force with \( h \) is practically the same since gradients are almost equal within experimental error. This is in accordance to theory since for Glare 2 the yield strength in the L direction is greater than the yield strength in the LT direction.

For Glare 3 however the yield strength is the same in both directions. From Graphs 15 and 16 this is only evident with the 2/1 lay-up. With the 3/2 lay-up some error was involved.

Another essential observation from Graphs 13 to 16 is that the gradient of the 3/2 lay-up is always steeper than the 2/1 lay-up. This implies that the difference in forces for \( h = 10 \) is larger than the difference in forces for \( h = 40 \). It is evident therefore that 3/2 lay-ups require a large force when \( h = 10 \) and three out of four times the material failed to sustain this force. On the contrary three out of four times, 2/1 lay-ups sustained the force applied to them. It is necessary therefore not to deform 3/2 lay-ups using small \( h \)'s.
- a good product
- Glare 2, 3/2 lay-up, LT
  - h=10mm
  - d=25mm
  - v=15mm

- a good product
- Glare 3, 3/2 lay-up, LT
  - h=40mm
  - d=25mm
  - v=15mm

- a bad product
- Glare 2, 3/2 lay-up, L
  - h=40mm
  - d=15mm
  - v=15mm

- a bad product
- Glare 3, 3/2 lay-up, L
  - h=40mm
  - d=0mm
  - v=15mm

Figure 13
Bend products obtained with the laminates.
6. CONCLUSIONS AND RECOMMENDATIONS

From the work carried out throughout this report it has become distinct that from the four possible variables that can influence the bending of fibre metal laminates, that is, the diameter of the cushion's cavity, the height of the block, the bend radius, and the yield strength of the material, the most dominant variable is the hole diameter. Hence it seems obvious that for the hole diameter the results obtained will be tabulated to facilitate any use which may be required of them. See Tables 3 and 4.

The height of the block also influenced the results although not as much as the hole diameter. Thus for completeness sake these results will be tabulated too. See Tables 5 and 6.

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>DIAMETER in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>GLARE 2</td>
<td></td>
</tr>
<tr>
<td>2/1</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>9.60</td>
</tr>
<tr>
<td>LT</td>
<td>10.00</td>
</tr>
<tr>
<td>3/2</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>12.20</td>
</tr>
<tr>
<td>LT</td>
<td>10.60</td>
</tr>
<tr>
<td>4/3</td>
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<tr>
<td>L</td>
<td>/</td>
</tr>
<tr>
<td>LT</td>
<td>11.50</td>
</tr>
</tbody>
</table>

v = 15mm, h = 40mm

Table 3

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>DIAMETER in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>GLARE 3</td>
<td></td>
</tr>
<tr>
<td>2/1</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>9.60</td>
</tr>
<tr>
<td>LT</td>
<td>10.00</td>
</tr>
<tr>
<td>3/2</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>11.60</td>
</tr>
<tr>
<td>LT</td>
<td>11.50</td>
</tr>
<tr>
<td>4/3</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>/</td>
</tr>
<tr>
<td>LT</td>
<td>13.90</td>
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</tbody>
</table>

v = 15mm, h = 40mm

Table 4
### Table 5

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>HEIGHT in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLARE 2</td>
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</tr>
<tr>
<td>2/1 L LT</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>3/2 L LT</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>4/3 L LT</td>
<td>/</td>
</tr>
</tbody>
</table>

\( V = 15\text{mm}, \ d = 25\text{mm} \)

### Table 6

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>HEIGHT in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLARE 3</td>
<td>0</td>
</tr>
<tr>
<td>2/1 L LT</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>3/2 L LT</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>4/3 L LT</td>
<td>/</td>
</tr>
</tbody>
</table>

\( V = 15\text{mm}, \ d = 25\text{mm} \)

**N.B.** The values within the tables correspond to the force that was required to bend the material. This force is measured in kN.

Also the symbol / in the tables indicates that that particular set-up was not examined.

The dotted line crossing Tables 3 to 6 separates the bad products from the good products in such a way that set-ups to the left of the dotted line result in bad products and set-ups to the right of the dotted line result in good products. Hence it is necessary that prior to deforming any of the fibre metal laminates mentioned in this report it is recommended to avoid set-ups that fall to the left of the dotted lines.
7. REFERENCES


C. Ciantar
31/09/93
8. GRAPHS

Force/Hole diameter Curve at h=20mm
v=15mm, material is 2024-T3

Graph 1

Force/Height Curve at v=15mm
r=4mm, material is 2024-T3

Graph 2
Graph 3

Graph 4
Force/ Yield strength Curve at h=20mm
v=15mm, d=25mm

Graph 5

Force/Bend radius Curve at h=20mm
v=15mm, material is 2024-T3

Graph 6
Force/Bend radius Curve at h=20mm
v=15mm, material is 6061-T6

Graph 7

Force/Bend radius Curve at h=20mm
v=15mm, material is 7075-T6

Graph 8
Force/Hole diameter Curve

\( v=15\text{mm}, h=40\text{mm}, \text{material direction is } L \)

Filled markers indicate a bad product

- Glare2, 2/1
- Glare2, 3/2

Graph 9

Force/Hole diameter Curve

\( v=15\text{mm}, h=40\text{mm}, \text{material direction is } LT \)

Filled markers indicate a bad product

- Glare2, 2/1
- Glare2, 3/2
- Glare2, 4/3

Graph 10
**Force/Hole diameter Curve**

$v=15\text{mm}, h=40\text{mm}, \text{material direction is L}$

Filled markers indicate a bad product

- - - Glare3, 2/1
- - - Glare3, 3/2

**Graph 11**

**Force/Hole diameter Curve**

$v=15\text{mm}, h=40\text{mm}, \text{material direction is LT}$

Filled markers indicate a bad product

- - - Glare3, 2/1
- - - Glare3, 3/2
- - - Glare3, 4/3

**Graph 12**
Force/Height Curve

v=15mm, d=25mm, material direction is L

Graph 13

Force/Height Curve

v=15mm, d=25mm, material direction is LT

Graph 14
Force/Height Curve
v=15mm, d=25mm, material direction is L

Filled markers indicate a bad product

Graph 15

Force/Height Curve
v=15mm, d=25mm, material direction is LT

Filled markers indicate a bad product

Graph 16
Graph 17

Force/Yield strength Curve for d=25mm
v=15mm, h=40mm, material direction is LT

Graph 18

Force/Yield strength Curve for d=25mm
v=15mm, h=40mm, material direction is L