Analysis And Comparison Of I-Beam And Solid Wing Spars

By Paul E. Best, EAA 2441

Drawings by Don Cookman

The other day while discussing amateur aircraft construction costs with some EAA friends, the subject of spar materials came up. As anyone who has built a plane realizes, spruce spar stock is not only somewhat hard to find but is rather expensive. It has to be ordered from one of a handful of firms which still carry this wood, and since commercial airplanes today use metal far more often, there is today not too much incentive for the commercial production and distribution of airplane spruce. Spar stock in sizes suitable for many light airplanes of about 30-foot span brings a price of a dollar or more per running foot, which means a total of from $50 to $100 per airplane. If this cost could be reduced, it would be a worthwhile saving.

Before World War One, spars were solid wood so slim as to warrant the label of "toothpick spars". During that war, most airplanes had finely routed I-beam spars, box spars and at times small solid spars. Between that time and the beginning of the second World War, the use of solid spars gradually became almost universal in small airplanes. The greatest single reason for this was manufacturers' interest in lowering the **labor cost.** Spruce trees are grown by Nature, not made in factories, and the cost of the wood to the ultimate consumer is due to the labor involved in felling the trees, cutting them up, working the wood and incorporating it into the finished airplane.

The plain solid spar requires fewer manufacturing steps than any other kind. After the wood has been selected and dried, about all that is required is to surface it on four sides to the required dimensions and drill it for bolt holes, and it is ready to go into an airplane wing. It is well worth noting that the structural efficiency of a plain solid spar is somewhat on the low side, not too important in smaller planes but important enough in larger ones to force designers to use built-up and routed spars of various kinds as airplane size goes above the smallest and lightest.

In regard to that statement, let us look at popular wooden-winged airplanes of the late 1930's. You would find plain solid spars in the popular little two-seaters of all makes, and in airplanes such as Waco biplanes where spar sizes were naturally small. But as soon as you looked at four-seaters such as the Fairchilds, Stinsons, Cessnas and others, you would find that it was standard practice to use either routed I-beams or built-up box beams.

It is also highly significant to remember that when lightplane production increased in volume, the cost and difficulty of obtaining good spruce in large quantities forced lightplane makers to change to other methods. For a while some popular makes used plain "solid" spars made by laminating together several pieces of short, cheap spruce. It is hard to find wood in long pieces that is truly perfect, so the laminating process allowed several shorter pieces to be assembled into an equivalent "solid" beam with less waste and material-hunting. In the end, aluminum spars were extruded for use in small planes like the Pipers. It was easier to extrude metal to the desired length, than to comb the forests for a few perfect trees, and of course the labor cost was kept low.

But, the amateur airplane builder is under far less pressure than the manufacturer to shave labor costs. He is...or should be...more concerned with the cost of the materials and their weight. In both these respects, the built-up I-beam excells. Routed I-beams may cost less as regards **labor** because of being made out of one piece of wood which is merely machined, but the **materials** cost is certainly high because of the thick plank which forms the raw material.

In Fig. 1 is shown the stress distribution in a spar. Maximum tension and compression occur at the outer edges, with no bending at all in the center. The only function of the wood in the center of a spar is to keep the outer areas separated. This load takes the form of a shear force as shown by the small vertical arrows. The depth and thickness of a solid wood spar are chosen to give the amount of wood required to resist tension and compression at the edges. These forces are much greater than the shear load, so in the center area of the spar there is really more wood than is needed. The I-beam spar places most of its material at the flanges where tension and compression require it, and in the center part eliminates all except that which is needed to resist shear forces. The distribution of material is more efficient. The box beam follows the same principle, but is often slightly heavier than the I-beam because it has more web material and internal blocking. Two one-sixteenth-inch shear webs are **not** equal in strength to one, one-eighth-inch web, due to the mathematics of sheet materials.

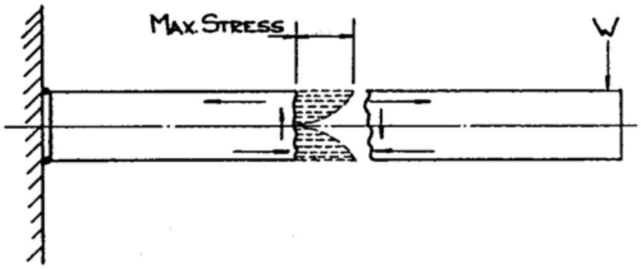


Fig. 1

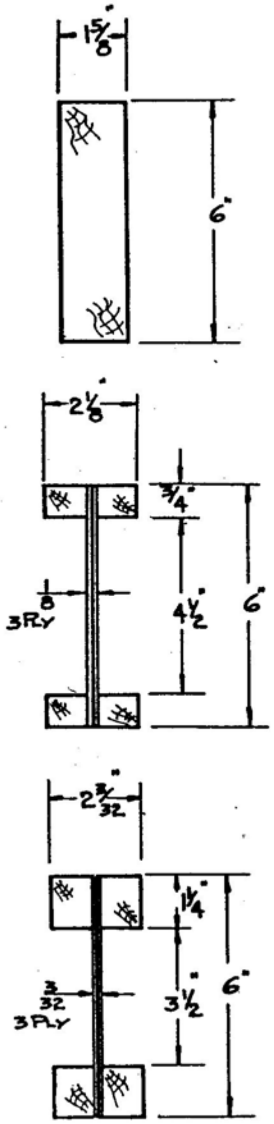
A box spar has the advantage of having a smooth external surface, which facilitates installation of wing ribs and compression members. But we must always remember that it has one great objection — it is not nearly so easy to inspect the interior to make absolutely sure there is no dry rot. As an airplane ages this point becomes ever more important. In contrast, practically nothing is hidden in a built-up I-beam.

In practice a built-up I-beam consists of five pieces, the four flange strips and the central web. Almost always there are a series of vertical stiffening strips, which prevent buckling of the web and at the same time provide handy rib attachment points.

A spar of usual length has its flange strips highly stressed by the bending loads, so a high-strength, lightweight material is wanted. Many materials and combinations of materials have been used in the past, such as oak, birch, maple, mahogany, fir, spruce, cypress, steel and aluminum. Each individual flange strip is likely to be of fairly small cross-sectional area, hence rather little material is needed with a lowering of cost. Old wing spars from some airplane, or a few dollars worth of mahogany planking, will provide the flange material needed for most amateur designs. The web piece does not experience concentrated loads and slight flaws need be no great concern. Perfectly safe, low-cost webs could be sawn from sheets of waterproof, clear-grain, knot-free marine grade mahogany plywood, which costs far less than aircraft plywood.

By now, some readers may be of doubtful mind, so we shall refer to some actual figures. In Fig. 2 is a comparison of one solid and two I-beam spars as regards weight, cost and dimensions for equivalent strength. See how the cost goes down — down — down! And see how the weight does likewise! At the cost of only a few nights' extra labor the amateur can gain very tangible benefits by using I-beams.

To compute the strength in bending of a spar of solid, I-, or box beam cross section, the formula Bending Stress= $M \times Y/I$, is used. These letters are: M = bending moment in inch pounds, Y = half the spar depth when the upper and lower flanges are of equal size, and I = the section Moment of Inertia, which is derived from the formula $I = B \times H^3/12$ minus $b \times h^3/12$. In the last formula the letters are: B = total spar width chordwise, b = total spar width minus web thickness, H = total spar height, h = total spar height minus the two flange heights or the gap between the flanges. The figure 3 after the letter H means to multiply H by itself 3 times.



Solid Spruce
$I = 33.75$

Lbs. per ft. 1.827
Cost per ft. $1.05
Bending Strength 60,000 in. lbs.

Spruce Caps and Birch Plywood
$I = 30.0$ approx.

Lbs. per ft. 1.340
Cost per ft. $0.97
Bending Strength 60,000 in. lbs.

Mahogany Caps and Plywood
$I = 23.0$ Approx.

Lbs. per ft. 1.200
Cost per ft. $0.65
Bending Strength 60,000 in. lbs.

Fig. 2
Beam Section

The above bending stress formula computes the maximum bending stress in pounds per square inch and the spar material must have an equal or larger yield or proportional limit bending stress. It will be noted that wood is the only material for which static bending stresses are tabulated. Therefore if the spar material is metal the material tensional yield stress is applied. (The "yield stress" is that which the material will withstand without developing a permanent bend. The "ultimate stress" for a material is that at which failure occurs, and this stress is always higher than the yield stress.)

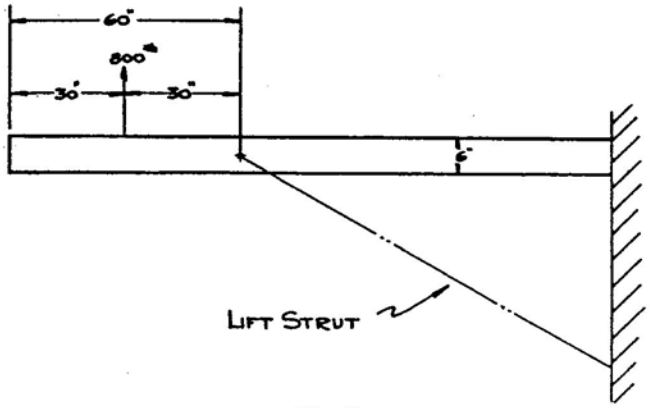


Fig. 3

To illustrate the use of these formulae we will compute the width of a spar of I-beam section, assuming the spar length to be 60 inches from the lift strut attachment or other support to the wing tip, and the spar load to be even along the span as in Fig. 3. The total spar load in the 60-inch span is 200 lbs. at the aircraft gross weight, and the load factor desired is 4 Gs, therefore the total spar load is 200 lbs. × 4 = 800 lbs. The bending moment will be the total load times the half span since the equal load distribution balances the load at the span mid point; 800 lbs. × 30 inches = 24,000 inch pounds. The airfoil selected will permit the spar depth to be 6 inches. We have ⅛ in. mahogany plywood for the web, and mahogany plank of one inch thickness, finished, which can be cut for spar caps. Referring to ANC bulletin #18 we find mahogany static bending fiber stress at proportional limit to be 8,800 pounds per sq. in. For some structural reason we decide the spar caps must be ¾ in. high and we know their width will be the total spar width minus the web of ⅛ in. divided by two. From the formula $BS\ (8800PSI) = \dfrac{M \times Y}{I}$ we see that I is still unknown therefore we start with the formula

$$BS \times I = \frac{M \times Y}{} \text{ or } I = \frac{M \times Y}{BS}.$$

Substituting our figures, $I = \dfrac{24000 \times 3}{8800}$ $I = 8.18$

and now we use this to find our spar width or "B", from the formula $I = \dfrac{B \times H^3}{12} - \dfrac{b \times h^3}{12}$

$$8.18 = \frac{B \times 6^3}{12} - \frac{b \times (6—1.5)^3}{12} =$$

$$8.18 = \frac{B \times 216}{12} - \frac{b \times 91.125}{12} =$$

18 B — 7.593 b.

Now since b = B minus the web or .125 inches, we have 8.18 = 18B — 7.593B + 7.593 × .125 or + .949 8.18 minus .949 = 7.231 = 10.407B

$$B = \frac{7.231}{10.407} = .694 \text{ in.}$$

In further explanation of the above conversion from 7.593b to 7.593B plus .949 — 7.593b = a minus quantity, therefore when multiplying the quantity (B minus .125) the product of the negative 7.593 times the negative .125 becomes a positive .949.

Now to proceed with the original problem. The total spar width computed is .694 inches, or .012 in. over 11/16 in. This is not very practical for wood working so we may increase it to .750 or ¾ in. The cap strip width will be $\frac{\text{¾ minus ⅛}}{2}$, or 5/16 in., and the height can remain at ¾ in.

In addition to the above problem, we must select the plywood web material for the required vertical shear strength, which is the panel lift force developed by the area outboard of any station desired to be checked and outboard of any wing support. From the data in ANC-18 the allowable shear forces for plywood beam webs has been computed and tabulated by type of material, thickness, web stiffener spacing and direction of the face grain. Reference to table No. 1. The three columns listed as A/B = 1., etc., reflect the ratio between the vertical inside distance between spar caps (A dimension) and the spanwise distance between web stiffeners (B dimension). The two columns of shear forces allowable under each A/B ratio headed by 0 deg. and 45t deg. reflect the values for the pertinent plywood with the face grain located parallel to the span (0 deg.) and at 45 deg. to the span.

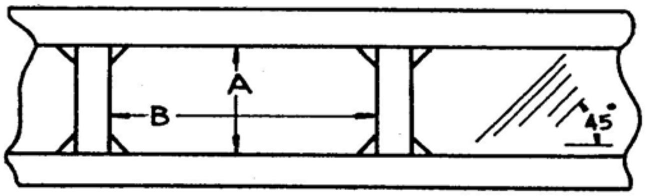


Table 1

Material	Thickness	A/B=1(4"x4")		A/B=.75 (4"x5.33)		A/B=.5(4x8")	
		0 Deg	45t Deg	0 Deg	45t Deg.	0 Deg	45t Deg
3 Ply							
Birch	.035	120#	175#	118#	172#	101#	151#
Birch	.070	423#	478#	340#	435#	254#	374#
Birch	.100	600#	815#	570#	770#	550#	592#
	.125	741#	1440#	732#	1270#	682#	1170#
3 Ply							
Yellow Poplar	.070	266#	333#	216#	302#	160#	262#
Yellow Poplar	.100	378#	580#	360#	546#	346#	422#
Yellow Poplar	.125	450#	960#	450#	870#	450#	745#
3-ply (or Douglas fir)							
Mahogany	.070	280#	434#	225#	395#	168#	338#
Mahogany	.100	395#	743#	375#	702#	362#	540#
Mahogany	.125	457#	1250#	457#	1130#	457#	970#

This entire table is based on a value of four in. for "A", the distance between flanges. The values listed if divided by four will be reasonably correct for the strength of each inch of web height between flanges, thereby allowing computation of web strength if an "A" dimension of other than four inches is required.

I-beam areas where root or lift strut fittings are attached, require the addition of filler blocks to give a solid section. The fillers must be tapered spanwise and carefully fitted and glued to the web and cap strips, to compensate for the material and strength removed by bolt holes. The filler length should be not less than the distance between web stiffeners, and the taper ratio not less than 8 to 1.

Vertical web stiffeners of square section and as thick as the cap strips are ample. The stiffener-to-cap-strip joint should preferably be made with corner glue blocks or plywood gussets on the sides to prevent any movement of the stiffener or web, as shown in the sketch near Table No. 1.

So there you are. I've given you the idea, and all the facts needed to put the idea to practical use. One word of caution, though — **calculate,** don't guess. Don't take chances on spars. If a spar breaks, the plane can't be force-landed because it is going to fall! ●

ADDENDA

Mr. Best has made an important suggestion for all of us who are interested in developing low-cost methods of amateur airplane construction. Too often we merely copy structural methods which were developed to fill production requirements! To make his article as valuable as possible we therefore include the following valuable data from government publications.

ANC - 18, "Design of Wood Aircraft Structures", is an excellent but hard-to-get book published by the government in World War Two to help designers of all-wood airplanes. Here are pertinent quotes relative to built-up spars:

"The wood-plywood beams are generally more efficient load-carrying member than the plain wood types (rectangular and routed). The box beam is often preferred because of its flush faces which allow easy attachment of ribs. The interior of box beams must be finished, drained and ventilated. Inspection of interiors is usually difficult. The shear load in a box beam is carried by two plywood webs. By checking shear web allowables it will be seen that for the same panel size a plywood shear panel half the thickness of another will carry **less** than half the shear load which can be carried by the thicker panel.

"The preceding statement points to an outstanding advantage of the I-beam since its shear strength is furnished by a single shear web rather than the two webs required of box or double-I beams. Also the I-beam produces a more efficient connection between the web and flange material than the box beam in cases where the web becomes buckled before the ultimate load is reached. This is because the clamping action on the webs tends to reduce the possibility of the tension component of the buckled web cleaving it away from the flange.

"Plain rectangular beams are generally used where the saving in weight of the wood-plywood types is not great enough to justify the accompanying increase in manufacturing trouble and cost.

"Routed beams are somewhat lighter than the plain rectangular type for the same strength but not so light as wood-plywood types. Usually the small weight saving does not justify the increase in fabrication effort and cost.

"In determining the relative efficiency of any beam type, reduction in allowable modulus of rupture due to form factors must be considered.

"Since the tension strength of a wood member is more adversely affected by any type of defect than is any other strength property, it is recommended that all tension flanges be laminated in order to minimize the effect of small hidden defects and to avoid the possibility of objectionable defects remaining hidden in a solid member of large cross section.

"Although square-laid plywood has been used extensively as shear webs in the past, the trend is to use diagonal plywood because it is more efficient as a shear-carrying material. It is desirable to lay all diagonal plywood of an odd number of plies so that the face grain is at right angles to the direction of possible shear buckles. In this way the shear web will carry appreciably higher buckling and ultimate loads because plywood is much stiffer in bending in the direction of the face grain and offers greater resistance to buckling if laid with the face grain across the buckles. This effect is greatest for 3-ply material.

(EDITOR'S NOTE: Observe that the above paragraph does not say that square-laid plywood **cannot** *be used; it says that diagonal plywood can be more efficient. This kind of advanced engineering would be useful in a large or fast airplane, but in an ultra-light, sight should not be lost of the very considerable price and procurement advantages of square-laid plywood. Obviously, web material made of some such plywood as 5-ply marine grade would have very little buckling trouble. The use of vertical stiffeners for rib attachment also divides up the web and helps take care of buckling.)*

"If splices must be made in the web material, a simple butt joint with backing plate is the poorest method. A simple scarf joint is much better, while a diagonal scarf joint is much the best. If splices are not made before assembling the web to the beam, blocking must be provided behind the splices to afford suitable backing for the clamps needed to secure adequate gluing pressure.

"Shear webs should be reinforced at frequent intervals by vertical stiffeners, as the shear strength of the web depends partly upon stiffener spacing. In addition to their function of stiffening the shear webs, the ability of beam stiffeners to act as flange spreaders is very important and care must be exercised to obtain a snug fit between the ends of the stiffeners and the beam flanges. External stiffeners for box spars are inefficient because of their inability to act as flange spreaders. Stiffeners are usually placed at every rib location to resist rib-assembly pressures. Any blocking used to carry fitting loads should be tapered as much as possible to avoid stress concentrations. It is desirable to include a few cross-banded laminations (Plywood? - Ed.) in all blocking in order to reduce the possibility of checking or tearing."

In addition to the above data, much valuable information can also be found in NACA Report 344, "The Design of Plywood Webs for Airplane Wing Beams", 1930, by G. W. Trayser. You can borrow a copy for a short time from National Aeronautics and Space Administration, Technical Information Division, Washington 25, D.C.

The editors of SPORT AVIATION feel that built-up I-beam spars offer distinct possibilities in lowering the materials cost of light amateur-built airplane construction, but for obvious reasons are publishing this article primarily as a thought-provoker. It is the responsibility of designers to do their own engineering and to perform any indicated strength tests before attempting flight in aircraft incorporating I-beam spars of experimental design.

Some Comparative Figures

Although Sitka spruce is considered standard for aircraft work, there is no law that says it must be used. The government has and still will approve other species when it can be shown that a satisfactory level of uniformity, strength and glue adhesion can be maintained. Douglas fir and mahogany (a name actually applying to several species of wood from Central America, Africa and the Philippines) are among the kinds which appear in lists of acceptable substitute, and it is informative to study this table of characteristics.

Wood	Wt. Per Cu. Ft.	Fiber Stress	Modulus Rupture	Modulus Elasticity	Ratio Working load to Max. load	Comp. Parallel to grain	Shear Strength	Hardness
Sitka Spruce	27	6200 lbs.	9,400	1300	7.8	840	750	440
Douglas Fir	34	8000 lbs.	11,500	1700	8.1	1300	810	620
African Mahogany	32	7900 lbs.	10,800	1860	8.0	1400	980	720

As a handy aid for calculating relative weights, here is a table of the average weight per foot for Sitka spruce strips:

Size, inches	Wt. per ft. in lbs.		
¼ x ¼	.012	¾ x 1	.141
¼ x ½	.024	¾ x 2	.282
¼ x 1	.046	¾ x 3	.423
⅜ x ¾	.024	¾ x 4	.564
½ x 1	.092	¾ x 5	.705
½ x 2	.184	¾ x 6	.846
½ x 2	.184	1 x 1	.189
½ x 3	.276	1 x 2	.378
½ x 4	.368	1 x 3	.567
½ x 5	.460	1 x 4	.756
½ x 6	.552	1 x 5	.945
¾ x ¾	.105	1 x 6	1.134

Addition And Correction To Analysis And Comparison Of I-Beam And Solid Wing Spars

The following is a correction and addition to Paul Best's Article that appeared in the April 1961 issue of SPORT AVIATION.

On page 28, right column, third paragraph, after the sentence "For some structural reason, we decide the spar caps must be ¾ in. high and we know their width will be the total spar width minus the web of ⅛ in. divided by two" - ADD Since the built up I beam is not similar to a solid beam, the listed static bending stress must be multiplied by a section form factor, Reference paragraph 2.30, ANC Bulletin #18.

The form factor for I beams of our type is given by the formula $FF = 0.58 \text{ plus } \frac{0.42 (K \times B - T}{B} \text{ plus } \frac{T)}{B}$

Where T = web thickness, B = Total spar width and K = a constant derived from table #1 which was extracted from ANC #18.

TABLE #1

Top Flange Height As A Percentage Of Total Spar Height

	10%	15%	20%	25%	30%	35%	40%	45%	50%
K =	.1	.16	.24	.32	.40	.48	.57	.65	.73

For this problem the factor FF equals .644 and the adjusted static bending stress at proportional limit is 8800 x .644 = 5667 PSI.

CORRECT THE BS in the formula computation $BS = \frac{M \times Y}{I}$ by inserting the adjusted figure above, 5667 PSI.

The corrected figure for I is 12.7.

SUBSTITUTE THE NEW FIGURE FOR I in the computation of the spar width "B" which is on top of page 29, resulting in an adjusted figure for "B" = 1.128 in. For practical wood working this is adjusted to 1-5/32 in. CORRECT THE computation of the cap strip width to

$$\frac{1\text{-}5/32 \text{ minus } 1/8}{2} = 33/64$$

To compare the revised I beam size, weight and price to an equal strength solid spruce beam reference the following table #2

	I BEAM	SOLID SPRUCE
Size —	6 in. x 1-5/32 in.	6 in. x 21/32 in.
Lbs./ft. —	0.539	0.724
Price/ft. —	60c	75c

In addition to the preceding computations, a *conservative* quickie method of finding the total flange size to obtain the cap strip size, is to divide the bending moment by the vertical height between the centers of the top and bottom caps. This gives the tension and compression loads on the flanges and assumes the web is not carrying any bending load. It will be noted that this is the old lever method.

Knowing the compression load, divide it by the material compression stress at proportional limit, mahogany is 4880 PSI, this gives the required flange area in sq. inches. The area is converted to cap size by dividing the area by the original cap height times two caps. ●

ATTACHING ALUMINUM FITTINGS TO WING SPARS

By Bill Wolleat, EAA 1953

I am submitting an exceptionally strong method of attaching aluminum fittings to wing spars or any other member where there are great shear forces.

I think this method is superior to the plug system in that it transmits the shear forces directly from the wood to the attachment fitting instead of to the bolts and thereby spreading the stress over a wider area of the metal fittings.

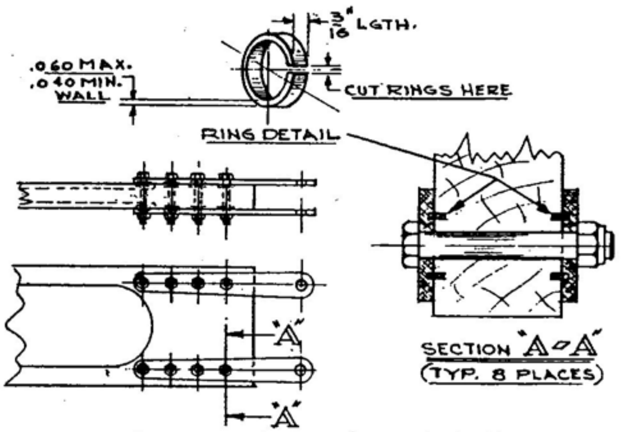
These rings should be cut from steel tubing of .040 to .060 and be cut about 3/16 in. long.

Now, using a fly cutter with a steel cutting bit to cut a groove to fit the thickness of your rings and a pilot bit slightly smaller than the holes you will use, set the stop gauge on your drill press and cut your grooves in the aluminum fittings to a depth of 1/16 in., then using the same cutting tool cut the grooves in the wood to ⅛ in.

All rings should be cut through on one side so that they will conform to the grooves better.

When rings are pressed into grooves there should be about 1/16 in. gap in the ring where it is cut open.

Use a diameter best suited to the size of fittings used.



FITTING TO SPAR ATTACH METHOD

DR:- S DZIK EAA NO.15