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REVISS Services
Quality and Regulatory Group

Technical Memorandum

Performance of the R7021 (GB 3981) Transport Container under IAEA Tie-Down Loads

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1. PURPOSE AND SCOPE

This document analyses the tie-down load paths in the R7021 transport container. It calculates stresses under worst-case accelerations and compares them and the associated fatigue life against the design criteria.

2. DESCRIPTION

The design consists of a shielded, stainless steel flask mounted on a pallet and protected from heat and impact by a jacket and top shield (Figure 1). The maximum gross weight of the design and key sub-assembly are tabulated below.

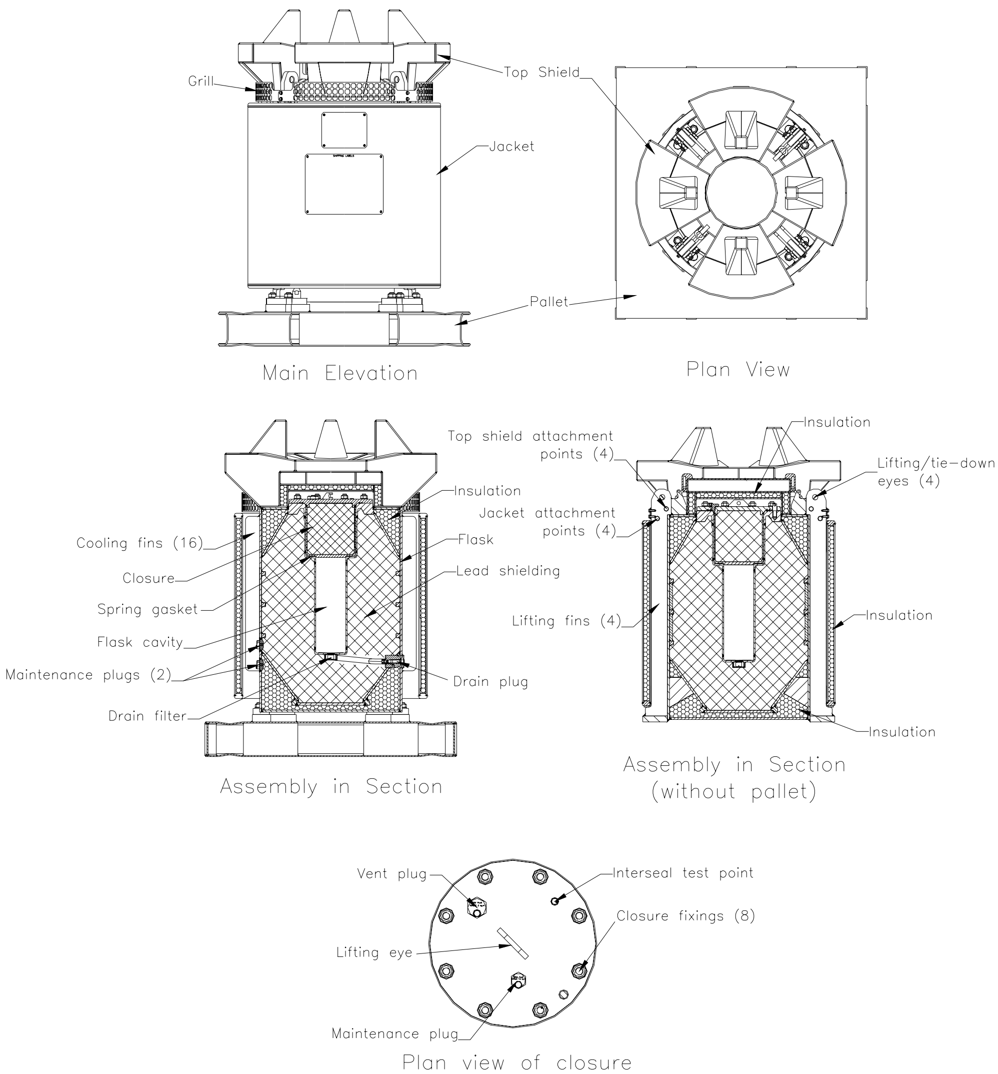

Figure 1: R7021 Assembly

Maximum Gross Assembly Weights (kg)	
Assembly (maximum gross weight)	4,600
Assembly minus pallet (maximum gross weight)	4,350

3. ASSESSMENT

3.1 CRITERIA

- The design strength (yield) shall not be exceeded when the assembly, at normal conditions of transport temperature, is subjected to the simultaneous application, in all three axes, of the worst case regulatory or modal acceleration factors.
- The ability of the design to comply with the Type B(U) requirements specified in TS-R-1 shall not be impaired should the tie-down points be overloaded to failure.
- No component shall be liable to fatigue failure from normal operation during the design life of 50 years.

3.2 ASSUMPTIONS

- Loads spread over more than one component are equally distributed.
- Tie-down members are aligned with the axis of the attachment point.
- Tie-down member shackle pins are diameter 28.6 mm (1⅛”).
- Special tie-down equipment is not used.
- The contribution from friction between components clamped together is ignored.
- Upward accelerations are ignored, as the load path is straight through the pallet into the flask.
- The contribution from the dowels between the pallet and flask is ignored.

3.3 ACCELERATION DATA

Acceleration data is taken from Table IV.1 of TS-G-1.1. The worst case resultant from any modal accelerations is the rail requirement.

Mode	Acceleration (g)			
	Longitudinal	Lateral	Vertical (down)*	Resultant $\sqrt{\Sigma a^2}$
Road	2	1	2	3.00
Rail	5	2	1	5.48
Sea	2	2	1	3.00
Air	1.5	1.5	5	5.43

* Allowing for gravity.

3.4 DESIGN STRENGTHS

Under normal conditions of transport the flask tie-down eyes are at a temperature of 93°C (RTM 120). The flask is fabricated from 1.4307 (304L) plate to BS EN 10088-2. The minimum room temperature yield strength of the components in the load path is 200 N/mm^2. This reduces to 178 N/mm^2 at a temperature of 93°C (using by proportion the reduction in design strength cited in PD 5500 for a similar grade steel (304-S11) up to 100°C).

The flask feet are at a temperature of 67°C (RTM 120). The yield strength also reduces to 178 N/mm^2 using the above method.

The pallet pad welds are at a maximum temperature of 67°C (RTM 120). The pallet is fabricated from S355 carbon manganese steel to BS EN 10025. The minimum room temperature yield strength is 400 N/mm^2 (drawing R7021/004). This reduces to 371 N/mm^2 at a temperature of 67°C (using by proportion the reduction in design strength cited in PD 5500 for a similar grade steel (223, 490A) up to 100°C).

Yield strength data for the Grade 8.8 carbon steel studs is taken from BS 3692 and reduced for the normal conditions of transport temperature of 67°C (using by proportion the reduction in design strength cited in PD 5500 up to 100°C).

A summary of the design strengths for each component in the tie-down load path is given below:

Element	Normal Conditions Temperature (°C)	Design Strength (N/mm^2)		
		Tension		Shear* (NCT)
		RT	NCT	
Tie-down eyes	93	200	178	103
Tie-down fin welds	93	200	178	103
Pallet pad welds	67	400	371	214
Flask studs	67	640	580	335
Flask-to-feet welds	67	200	178	103

* Using a factor of 0.577 on tensile strength based on Von Mises' theorem.

3.5 LOAD PATH

Horizontal loads from the chocks are taken directly into the pallet and into the flask fixings and feet welds. Vertical loads from toppling moments and vertical accelerations are taken through the tie-down eyes and their attaching welds into the flask body.

3.6 RESTRAINED MASSES

The mass restrained by each element in the load path is:

Element	Restrained Mass (kg)
Tie-down eyes	4,600
Tie-down fin welds	
Pallet pad welds	4,350
Flask studs	
Flask-to-feet welds	

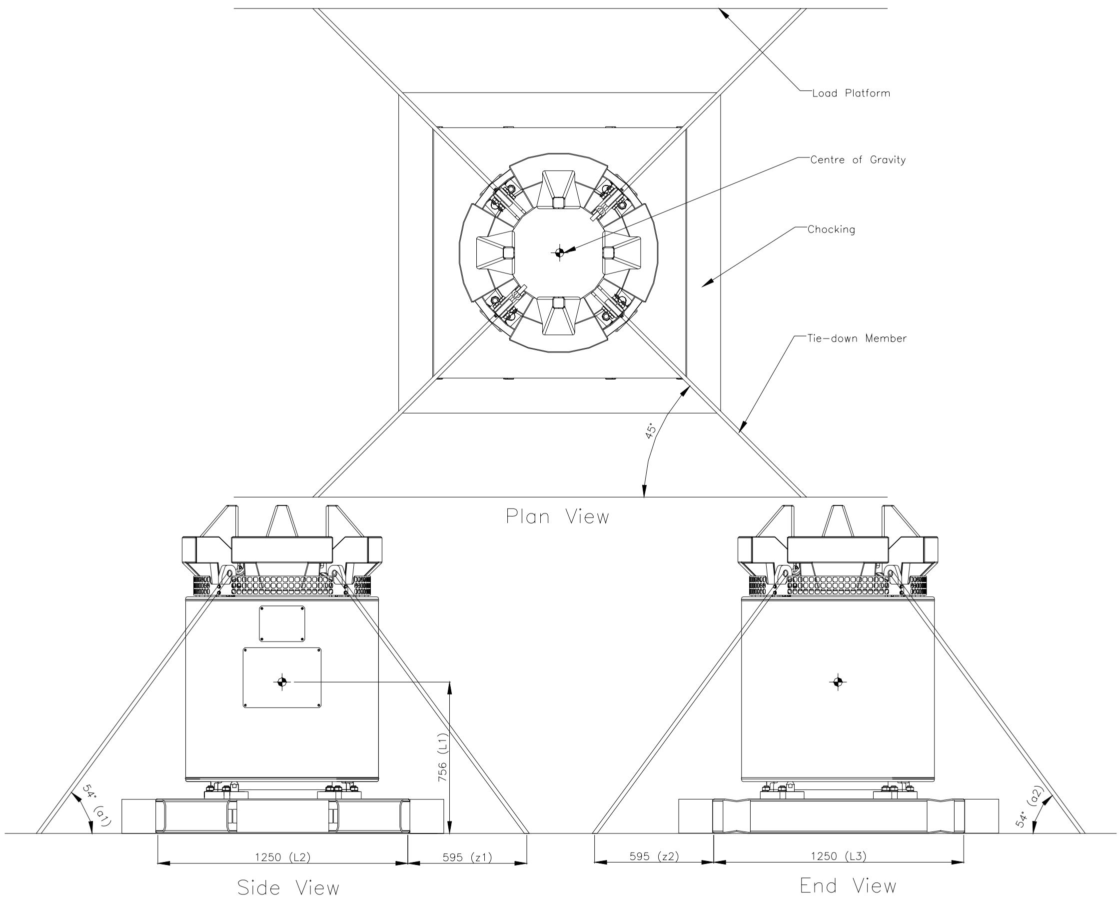

Figure 2: R7021 Tie-down Arrangement

3.7 RESTRAINT LOADS

The maximum tie-down load in each element in each of the three axes is therefore:

<table>
<tr><td rowspan="2">Element</td><td colspan="3">W, Restraint Load (kN)</td></tr>
<tr><td>Longitudinal (W_{lon})</td><td>Lateral (W_{lat})</td><td>Vertical down (W_{ver})</td></tr>
<tr><td>Tie-down eyes</td><td rowspan="2">226</td><td rowspan="2">90.3</td><td rowspan="2">45.1</td></tr>
<tr><td>Tie-down fin welds</td></tr>
<tr><td>Pallet pad welds</td><td rowspan="3">213</td><td rowspan="3">85.3</td><td rowspan="3">42.7</td></tr>
<tr><td>Flask studs</td></tr>
<tr><td>Flask-to-feet welds</td></tr>
</table>

4. ANALYSIS

4.1 TIE-DOWN EYES

The analysis will consider the load generated by each acceleration in turn and then combine them to arrive at the maximum stress generated in each component in the tie-down eye load path.

4.1.1 Stresses in tie-down eyes

(a) Longitudinal acceleration loads are taken primarily by the chocking but a toppling moment will be generated which will create an upwards force, W_1, on each of the two eyes at the opposite end. The force is proportional to the height of the centre of gravity and inversely proportional to the distance from the tie-down point to the chocked edge of the pallet. This force is resisted however by gravity acting downwards on the package. The symmetry of the design puts the centre of gravity at its mid-length and mid-width and so the gravitational force may be taken as one quarter of the package mass acting at each corner. The load on each eye, W_1, is therefore:

$$W_1 = \frac{(W_{lon} \times L_1) - (M \times g \times 0.5 \times L_2)}{N \times (L_2 + z_1) \times \sin a_1 \times \sin a_2}$$

where

W_{lon} = longitudinal acceleration load = 226 kN
L_1 = height of package CoG = 0.756 m
M = package mass = 4,600 kg
g = gravitational acceleration = 9.81 m/s^2
L_2 = floor length of pallet = 1.25 m
z_1 = longitudinal distance from pallet to tie-down point = 0.595 m
N = number of tie-down eyes under load = 2
a_1 = tie-down angle from horizontal (viewed from the side) = 54°
a_2 = tie-down angle from horizontal (viewed from the end) = 54°

thus

$$W_1 = \frac{(226 \times 10^3 \times 0.756) - (4{,}600 \times 9.81 \times 0.5 \times 1.25)}{2 \times (1.25 + 0.595) \times 0.809 \times 0.809} = 59.1 \text{ kN}$$

(b) Lateral acceleration loads are taken primarily by the chocking but a toppling moment will be generated which will create an upwards force, W_2, on each of the two eyes on the opposite side. The force is proportional to the height of the centre of gravity and inversely proportional to the distance from the tie-down point to the chocked edge of the pallet. Again the force is resisted by gravity. The load on each eye, W_2, is therefore:

$$W_2 = \frac{(W_{lat} \times L_1) - (M \times g \times 0.5 \times L_3)}{N \times (L_3 + z_2) \times \sin a_1 \times \sin a_2}$$

where

W_{lat} = lateral acceleration load = 90.3 kN
L_3 = floor width of pallet = 1.25 m
z_2 = lateral distance from pallet to tie-down point = 0.595 m
N = number of tie-down eyes under load = 2
a_1 = tie-down angle from horizontal (viewed from the side) = 54°
a_2 = tie-down angle from horizontal (viewed from the end) = 54°

thus

$$W_2 = \frac{(90.3 \times 10^3 \times 0.756) - (4{,}600 \times 9.81 \times 0.5 \times 1.25)}{2 \times (1.25 + 0.595) \times 0.809 \times 0.809} = 16.6 \text{ kN}$$

(c) Vertical acceleration loads create an upwards force on all of the tie-down eyes. The load on each eye, W_3, is therefore:

$$W_3 = \frac{W_{ver}}{N \times \sin a_1 \times \sin a_2}$$

where
W_{ver} = vertical acceleration load = 45.1 kN
N = number of tie-down eyes under load = 4
a_1 = tie-down angle from horizontal (viewed from the side) = 54°
a_2 = tie-down angle from horizontal (viewed from the end) = 54°

thus $$W_3 = \frac{45.1 \times 10^3}{4 \times 0.809 \times 0.809} = 17.2 \text{ kN}$$

(d) Bearing stress in eye:
The combined load from each of the three accelerations above is the sum of all three. The load is resisted by the tie-down member and its shackle pin generates compressive (bearing) stress in the eye (see Fig 3). The stress, S, is therefore:

$$S = \frac{W_1 + W_2 + W_3}{A}$$

where
A = projected contact area of shackle pin = D x L

Where
D = shackle pin diameter = 28.6 mm
L = length of contact = 25.0 mm

thus
A = 28.6 x 25.0 = 715 mm^2

thus $$S = \frac{(59.1 + 16.6 + 17.2) \times 10^3}{715} = 130 \text{ N/mm}^2$$

(e) Pull-out stress in eye:
The load is resisted by the tie-down member and its shackle pin may be considered to create two shear planes (Fig 3) in the eye as it attempts to pull through the eye plate. The shear stress, S_1, in these planes is therefore:

$$S_1 = \frac{W_1 + W_2 + W_3}{A_1}$$

where
A_1 = total area of shear planes = (25 x 59.0) + (25 x 84.1) = 3,580 mm^2

thus $$S_1 = \frac{(59.1 + 16.6 + 17.2) \times 10^3}{3{,}580} = 25.9 \text{ N/mm}^2$$

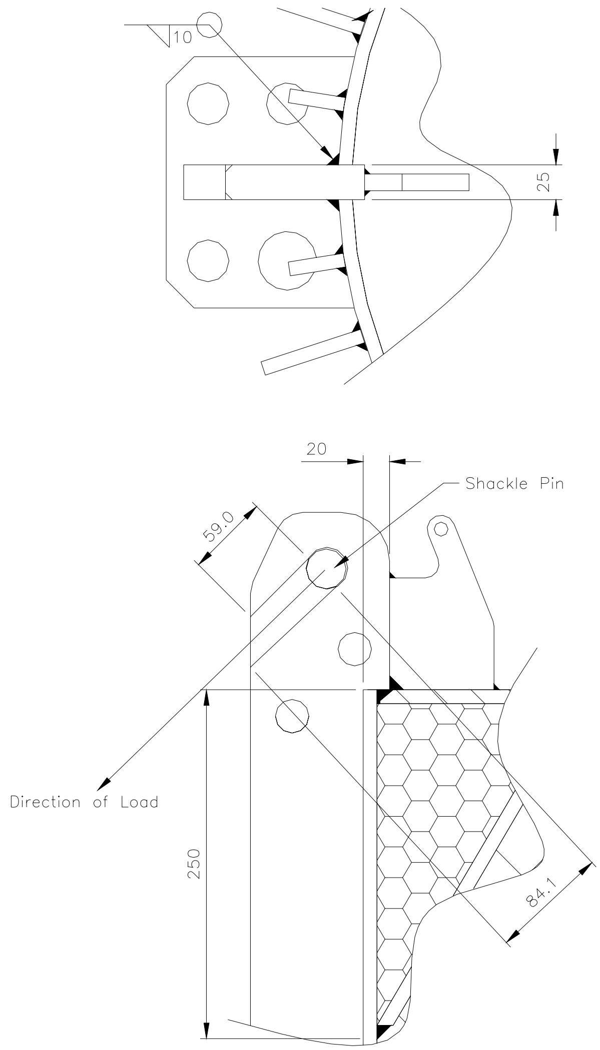

Figure 3: Tie-down eye details

4.1.2 Stress in tie-down fin weld

The load from each acceleration will be the same as above therefore the maximum load will be the sum again. The shear stress, S_2, generated in the fin weld is therefore:

$$S_2 = \frac{W_1 + W_2 + W_3}{A_2}$$

where

A_2 = cross-sectional area of weld = l x t

where

l = weld length = $2(250^* + 20)$ = 540 mm

t = weld throat width = 10 x 0.707 = 7.07 mm

*(stressed vertical length of weld is taken as 250mm on each side of the fin)

thus A_2 = 540 x 7.07 = 3,820 mm^2

thus $S_2 = \frac{(59.1 + 16.6 + 17.2) \times 10^3}{3{,}820} = 24.3\ N/mm^2$

4.2 PALLET

The flask is supported on a square pallet fabricated from carbon steel plate. The two are held together with twelve carbon steel, M24 studs and nuts. The studs are secured into carbon steel pads that are welded to the main pallet surface. The studs and welds are subject to shear loads from horizontal accelerations.

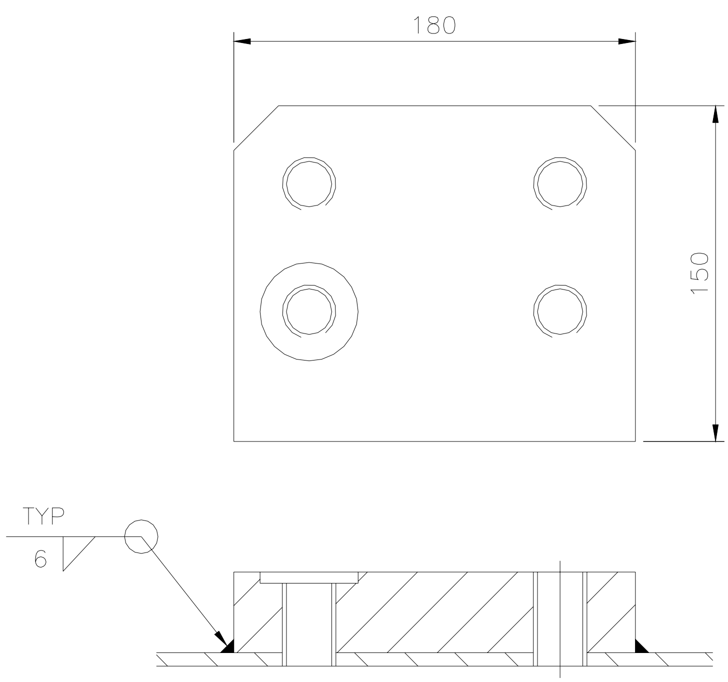

Figure 4: Pallet pad details

4.2.1 Pallet welds

(a) Longitudinal acceleration loads generate a longitudinal shear stress, S_3, in the welds:

$$S_3 = \frac{W_{lon}}{A_3}$$

where
A_3 = N x A

where
N = number of pads = 4
A = cross-sectional area of weld = l x t

where
l = weld length = 2(180 + 150) = 660 mm
t = weld throat width = 6 x 0.707 = 4.24 mm

thus $A_3 = 4 \times (660 \times 4.24) = 11{,}200\ mm^2$

and $S_3 = \dfrac{213 \times 10^3}{11{,}200} = 19.0\ N/mm^2$

(b) Lateral acceleration loads generate a lateral shear stress, S_4, in the welds:

$$S_4 = \frac{W_{lat}}{A_3}$$

thus $S_4 = \dfrac{85.3 \times 10^3}{11{,}200} = 7.62\ N/mm^2$

(c) Vertical acceleration loads generate no stresses in the welds.

(d) Load combination stress
The maximum stress is found when the three acceleration loads are applied simultaneously. The maximum normal and shear stresses are found using the tri-axial stress analysis methodology. Thus:

S_x = normal longitudinal stress = 0
S_y = normal vertical stress = 0
S_z = normal lateral stress = 0
S_{xy} = vertical shear = 0 N/mm^2
S_{yz} = lateral shear = 7.62 N/mm^2
S_{zx} = longitudinal shear = 19.0 N/mm^2

A $= S_x + S_y + S_z = 0$
B $= S_x.S_y + S_y.S_z + S_z.S_x - S_{xy}^2 - S_{yz}^2 - S_{zx}^2 = -419$
C $= S_x.S_y.S_z + 2.S_{xy}.S_{yz}.S_{zx} - S_x.S_{yz}^2 - S_y.S_{zx}^2 - S_z.S_{xy}^2 = 0$
D $= A^2/3 - B = 419$
E $= A \times B/3 - C - 2A^3/27 = 0$
F $= \sqrt{(D^3/27)} = 1{,}651$
G $= \cos^{-1}(-E/2F) = 90.0°$
H $= \sqrt{(D/3)} = 11.8$

the principal stresses are therefore:
I $= 2.H.\cos(G/3) + A/3 = 20.5\ N/mm^2$
J $= 2.H.\cos(G/3 + 120°) + A/3 = -20.5\ N/mm^2$
K $= 2.H.\cos(G/3 + 240°) + A/3 = 0\ N/mm^2$

S_5, the maximum principal normal (tensile) stress, is therefore 20.5 N/mm^2

S_6, the maximum shear stress, is $0.5(S_5 - S_{min}) = 20.5\ N/mm^2$

4.2.2 Pallet fixings

(a) Longitudinal acceleration loads generate a longitudinal shear stress, S_7, in the fixings:

$$S_7 = \frac{W_{lon}}{A_4}$$

where

$A_4 = N \times A_t$

where

N = number of bolts = 12

A_t = tensile stress area of M24 bolt = 353 mm^2 (BS 3643)

thus $A_4 = 12 \times 353 = 4{,}240\ mm^2$

and $S_7 = \frac{213 \times 10^3}{4{,}240} = 50.2\ N/mm^2$

(b) Lateral acceleration loads generate a lateral shear stress, S_5, in the flask fixings:

$$S_8 = \frac{W_{lat}}{A_4}$$

thus $S_8 = \frac{85.3 \times 10^3}{4{,}240} = 20.1\ N/mm^2$

(c) Vertical acceleration loads generate no stresses in the fixings.

(d) Load combination stress

The maximum stress is found when the two acceleration loads are applied simultaneously. The maximum normal and shear stresses are found using the tri-axial stress analysis methodology. Thus:

S_x = normal longitudinal stress = 0

S_y = normal vertical stress = 0

S_z = normal lateral stress = 0

S_{xy} = vertical shear = 0

S_{yz} = lateral shear = 20.1 N/mm^2

S_{zx} = longitudinal shear = 50.2 N/mm^2

$A = S_x + S_y + S_z = 0$

$B = S_x.S_y + S_y.S_z + S_z.S_x - S_{xy}^2 - S_{yz}^2 - S_{zx}^2 = -2{,}924$

$C = S_x.S_y.S_z + 2.S_{xy}.S_{yz}.S_{zx} - S_x.S_{yz}^2 - S_y.S_{zx}^2 - S_z.S_{xy}^2 = 0$

$D = A^2/3 - B = 2{,}924$

$E = A \times B/3 - C - 2A^3/27 = 0$

$F = \sqrt{(D^3/27)} = 30{,}430$

$G = \cos^{-1}(-E/2F) = 90°$

$H = \sqrt{(D/3)} = 31.2$

the principal stresses are therefore:

$I = 2.H.\cos(G/3) + A/3 = 54.1\ N/mm^2$

$J = 2.H.\cos(G/3 + 120°) + A/3 = -54.1\ N/mm^2$

$K = 2.H.\cos(G/3 + 240°) + A/3 = 0\ N/mm^2$

S_9, the maximum principal normal (tensile) stress, is therefore 54.1 N/mm^2

S_{10}, the maximum shear stress, is $0.5(S_9 - S_{min}) = 54.1$ N/mm^2

4.3 Flask and Supports

The flask is supported on four feet that are welded to its base. The feet welds will be subject to shear loads generated by horizontal accelerations.

4.3.1 Flask feet welds

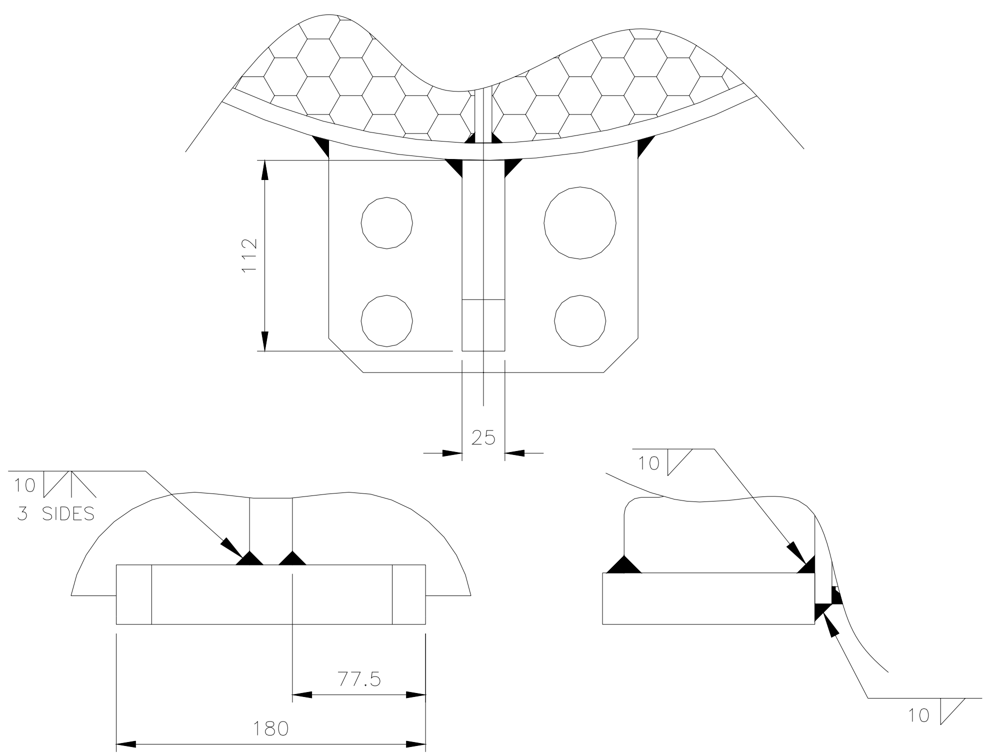

Figure 5: Flask feet details

(a) Longitudinal acceleration loads generate a longitudinal shear stress, S_{11}, in the welds:

$$S_{11} = \frac{W_{lon}}{A_5}$$

where

A_5 = N x A

where

N = number of feet = 4

A = cross-sectional area of weld = l_1 x t_1 + l_2 x t_2

where

l_1 = fillet weld length = 2 x 77.5 + 180 = 335 mm

l_2 = weld length = 2 x 112 + 25 = 249 mm

t_1 = fillet weld throat width = 10 x 0.707 = 7.07 mm

t_2 = weld throat width = 10 mm

thus A_5 = 4 x (335 x 7.07 + 249 x 10) = 19,400 mm^2

and $$S_{11} = \frac{213 \times 10^3}{19{,}400} = 11.0 \text{ N/mm}^2$$

(b) Lateral acceleration loads generate a lateral shear stress, S_4, in the flask fixings:

$$S_{12} = \frac{W_{lat}}{A_3}$$

thus $$S_{12} = \frac{85.3 \times 10^3}{19{,}400} = 4.40 \text{ N/mm}^2$$

(c) Vertical acceleration loads generate no stresses in the fixings.

(d) Load combination stress

The maximum stress is found when the two acceleration loads are applied simultaneously. The maximum normal and shear stresses are found using the tri-axial stress analysis methodology. Thus:

S_x = normal longitudinal stress = 0

S_y = normal vertical stress = 0

S_z = normal lateral stress = 0

S_{xy} = vertical shear = 0

S_{yz} = lateral shear = 4.40 N/mm^2

S_{zx} = longitudinal shear = 11.0 N/mm^2

A $= S_x + S_y + S_z = 0$

B $= S_x.S_y + S_y.S_z + S_z.S_x - S_{xy}^2 - S_{yz}^2 - S_{zx}^2 = -140$

C $= S_x.S_y.S_z + 2.S_{xy}.S_{yz}.S_{zx} - S_x.S_{yz}^2 - S_y.S_{zx}^2 - S_z.S_{xy}^2 = 0$

D $= A^2/3 - B = 140$

E $= A \times B/3 - C - 2A^3/27 = 0$

F $= \sqrt{(D^3/27)} = 320$

G $= \cos^{-1}(-E/2F) = 90°$

H $= \sqrt{(D/3)} = 6.8$

the principal stresses are therefore:

$I = 2.H.\cos(G/3) + A/3 = 11.8\ N/mm^2$

$J = 2.H.\cos(G/3 + 120°) + A/3 = -11.8\ N/mm^2$

$K = 2.H.\cos(G/3 + 240°) + A/3 = 0\ N/mm^2$

S_{13}, the maximum principal normal (tensile) stress, is therefore 11.8 N/mm^2

S_{14}, the maximum shear stress, is $0.5(S_{13} - S_{min}) = 11.8\ N/mm^2$

4.6 SUMMARY OF STRESSES

The stress levels and safety factors in the various elements of the R7021 structure under the worst case combined tie-down accelerations are summarised as follows:

Structural Element	Design Strength (N/mm^2)	Stress Type	Maximum Stress (N/mm^2)	Safety Factor
Tie-down eyes	178	bearing	130	1.37
	103	shear	25.9	1.80
Fin welds	103	shear	24.3	3.98
Pallet-to-pad welds	214	shear	20.5	10.4
Flask-to-pallet studs	335	shear	54.1	6.19
Flask feet welds	103	shear	11.8	8.73
Minimum Safety Factor				1.37

5. FATIGUE

TCSC 1006 Appendix, Section d), provides a method for demonstrating the likelihood of fatigue failure over the design life of a transport container. By dividing the range of accelerations experienced in any particular mode of transport into discreet subsets it is possible to calculate the stress range for each subset and hence the allowable number of cycles. Knowing the actual number of cycles likely to be experienced in the container's design life it is then possible to calculate the proportion of the fatigue life "used up" by each subset. A satisfactory fatigue case is made when the sum of the proportions is less than 1. The calculations are laid out in the Table below.

This container is shipped almost exclusively by road and sea. Of these two modes, road transport is by far the more demanding for fatigue considerations. TCSC 1006 Table 6 gives the frequency of different longitudinal, lateral and vertical accelerations recorded during a road shipment of a 20' ISO freight container with a 10 tonne load.

The highest non-compressive stress in the R7021 structure is the shear stress generated in the flask-to-pallet studs (see 4.2.2 (d)). The stress at other accelerations is calculated using the method in Section 4.2.2 of this document. Equation C-5 in PD 5500, Annex C, paragraph 3.1.2 is then used to calculate the allowable number of cycles at each stress.

The actual number of cycles is based on an estimate of the container's lifetime usage. UK shipments are entirely by road and on average 300 miles round trip. International shipments are made by sea to the nearest port, with road journeys at either end. The average distance from port to final destination does not exceed 400 miles. Therefore an average road round trip for the R7021 may reasonably be taken as 1,000 miles. Hence, for a nominal design life of fifty years and 12 shipments per year, a container could be shipped a total of 600,000 miles in its lifetime. Assuming an average speed of 30 mph, the lifetime duration therefore would be 20,000 hours.

Table 6 gives the total number of cycles per 1,000 hours for each acceleration (load case) so these are multiplied by twenty to obtain the total number of cycles. Dividing the total number of cycles by the allowable number of cycles gives the fatigue life proportion for each load case:

Axis	Acceleration (g)	Stress range (N/mm^2)	Allowable number of cycles	Number of cycles per 1,000 hrs	Number of cycles for 20,000 hrs	Proportion of allowable cycles
Longitudinal	0.4	2.0*	NA	1.12E+07	2.23E+08	0.00E+00
	0.8	4.0*	NA	1.93E+06	3.86E+07	0.00E+00
	1.2	6.0	7.23E+08	9.95E+04	1.99E+06	2.75E-03
	1.6	8.0	3.05E+08	5.36E+03	1.07E+05	3.52E-04
	2	10.0	1.56E+08	491	9.82E+03	6.29E-05
Lateral	0.2	0.8*	NA	1.12E+07	2.23E+08	0.00E+00
	0.4	1.6*	NA	1.93E+06	3.86E+07	0.00E+00
	0.6	2.4*	NA	9.95E+04	1.99E+06	0.00E+00
	0.8	3.2*	NA	5.36E+03	1.07E+05	0.00E+00
	1	4.0*	NA	491	9.82E+03	0.00E+00
Vertical	0.4	0.0*	NA	1.12E+07	2.23E+08	0.00E+00
	0.8	0.0*	NA	1.93E+06	3.86E+07	0.00E+00
	1.2	0.0*	NA	9.95E+04	1.99E+06	0.00E+00
	1.6	0.0*	NA	5.36E+03	1.07E+05	0.00E+00
	2	0.0*	NA	491	9.82E+03	0.00E+00
Sum of fatigue life proportions						3.17E-03

* Does not exceed 5 N/mm^2, hence fatigue analysis is not required (para. C.2.2, PD 5500).

It is evident therefore that the tie-down points are not at risk from fatigue failure during the design life.

6. CONCLUSIONS

- Design Criteria: The R7021 transport container meets its design criteria and the tie-down requirements for Type B(U) packages as specified in TS-R-1 and TS-G-1.1 with a minimum factor of safety of 1.37.
- Overload: Should the R7021 be overloaded to the point of failure the tie-down eyes would fail first leaving all key components intact. This would not impair its ability to meet all other Type B(U) requirements specified in TS-R-1.
- Fatigue: No component is at risk from fatigue failure from tie-down loads during the design life.

7. REFERENCES

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