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Characterization of Collet Lock for Umbilical System

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Abstract
"Umbilical" systems for a launch vehicle analogous to its biological meaning, serves as a separable conduit between vehicle and launch pad enabling various servicing needs. These systems are designed to separate at a pre-determined time, prior to launch or during lift-off. For any umbilical system, a flawless performance with respect to reliable servicing, separation and safe & timely retraction of separated half from launch vehicle is essential. Paper deals with experimental characterization performed on a heavy duty collet mechanism, which is the locking system for cryogenic umbilicals. The mechanism holds flight and ground segments of umbilicals avoiding premature release and should be a fast release when commanded to separate. The particular system which operates at extreme range of pressure & temperature gradient is used for fluid & pneumatic servicing of cryogenic stage and gets separated by initiating a pyro device. A series of tests were conducted to characterize performance of collet lock system and to optimize torque & release load. Results were analyzed and suitable modifications were made.
Keywords: *Cryogenic Umbilicals, Collet Lock, Tie Rod, Pyro Puller, Separation, Flight Segment.*

1. Introduction

Space technology is an excellent venue of multidisciplinary technology. Launch sequence includes breath-taking functions like ignition of solid/ liquid engines and fault free performance of various components, systems and modules. Umbilical systems [1&2] cater to various servicing requirements (electrical, propellant servicing, environmental conditioning services etc). These systems take inputs from a dedicated facility called Umbilical Tower (UT) and enable servicing of vehicle at launch pad. Once intended servicing operations are completed, ground segment separates from vehicle by activation of mechanism. Cryogenic stages of ISRO also employ umbilical systems for fluid servicing. It is a complex system, as it has to operate under extremely low temperatures & thermal gradients, vast range of fluid pressures (33 MPa to 0.15 MPa) with stringent leak tightness & safety requirements. Verification of design margins and reliability of such a system depends on the experiments & qualification trials done before flight induction. Collet lock mechanism holds flight & ground segment together against separation loads exerted due to fluid pressure, ejection & fluid hoses' loads etc. until release of piston out of collet thereby separating ground segment. The piston is primarily released by a pyro device. In case the pyro fails, it is mechanically pulled (secondary) by vehicle lift-off based traction.

2. About Umbilical System

Umbilical systems essentially consist of three subsystems namely flight segment (FS), ground segment (GS) and locking cum separation mechanism. Flight segment is rigidly attached to launch vehicle which lifts off along with vehicle. Flight segment is a machined plate with stage fluid interfaces on one side and highly finished surface on the other side. It also houses Automatic Sealing Devices (ASD) in specified fluid lines to provide redundant sealing. ASDs are pushed to open while in mated condition to facilitate fluid servicing and get automatically closed after ground segment separation to prevent fluid loss in case of upstream flow valve leakage.

Ground Segment houses all fluid servicing lines and has critical sealing interfaces to flight segment & launch pad hoses on either ends. Hydro-formed stainless steel bellows are provided in fluid lines to compensate for thermal contraction. A collet based lock mechanism [3], [4] holds the flight & ground segment in mated condition during servicing and resists all forms of separation loads. Separation mechanism generates necessary force to release the collet lock at intended time, thereby separating ground segment. Separation system [5] is provided with dual mode redundancy, primary mode being initiated by firing a pyro device. Pyro device employs explosive substance which produces required energy to release the piston out of collet and thereby enables separation. This event is part of Auto Launch Sequence *(ALS)* and is timed to occur at a predetermined event before lift-off or at T_0 after sensing the vehicle lift off. Refer Fig.1 for 3D model of umbilical unit.

In case of pyro device failure, the separation is affected by secondary pull by a pneumatic cylinder (in case of pre-launch Umbilical) or traction pull by vehicle lift (in case of lift-off Umbilical). In case of pre-launch Umbilical, a cable connects the Pneumatic Cylinder piston to collet piston through pyro puller & Tie rod. When pneumatic cylinder is charged with high pressure gas, it develops adequate load to release the collet.

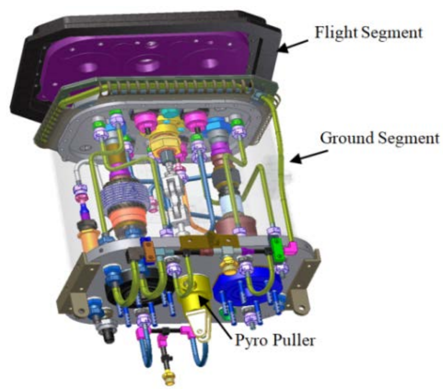

Fig. 1 3D Model of Typical Umbilical unit

In case of lift-off Umbilical, a traction cable is connected to piston of collet lock by same means & the other end is fixed to the Umbilical Tower. Based on the vehicle sway at launch pad and release time, designed slackness is provided in both these cases. Once this slackness is consumed by piston movement/vehicle travel at lift-off, the cable gets taut and generates force to release collet piston.

3. Collet Lock Mechanism: Configuration

Collet lock mechanism in its simplest analogy can be considered as a collapsible bolt. In umbilical system, it holds flight & ground segments and while torquing, the tensile load generated in collet acts as compressive load between two mating segments. Compressive load generated between segments should ensure sufficient margin over the separation loads. Collet is a precisely machined hollow cylinder with 16 numbers of identical cantilever beams, which deflect upon experiencing radial bending force.

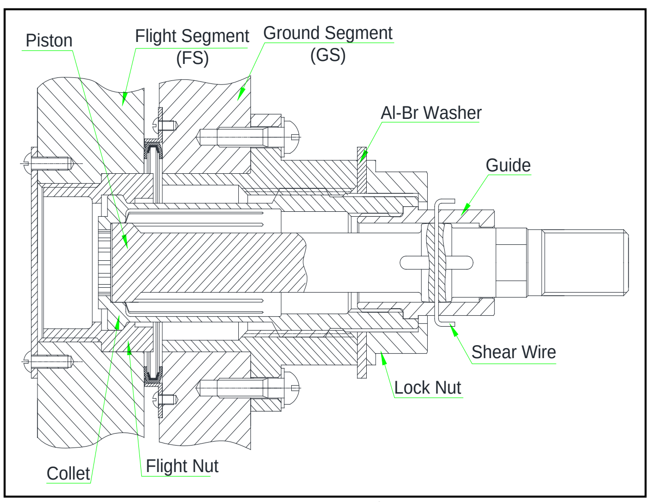

Fig.2 Collet lock configuration

During assembly the collet head is compressed and inserted into a flight nut. Geometry of flight nut to collet has designed angular profile which helps in producing radial load to deflect collet beams, thus enabling release. Flight nut has threaded male interface to flight segment. During assembly, female spline of ground segment guides with male spline of collet. When lock nut is torqued it induces tensile load in collet beams and thereby compressive load between segments. The compressive/clamping force thus produced has two components (Refer Fig.2). Axial component holds ground segment against separation loads. Radial component pushes collet beams inward trying to collapse, but is prevented by piston. When the piston is commanded to release, collet beams collapse and come out of flight nut leading to separation.

4. Preliminary Design & Analysis

Load carrying capacity & reliable release are primary criterions for collet. Total separation load accounts for spring ejection loads, fluid pressure load during servicing, fluid hose loads at launch pad due to vehicle sway and loads generated from umbilical retrieval mechanism. Factors to be considered while designing collet locks are; i) Maximum separation load, ii) Clamping force to be generated through collet, iii) Torque needed to develop required clamping force, iv) Radial load required to deflect & release collet beams and v) Pull load to release piston.

Total separation load came to 50 kN and hence input for collet design load with margin was finalised as 75 kN. Configuration study was done based on the above loads for specified requirements of envelope and assembly.

4.1 Material Selection

Considering the heavy duty collet & operating fluids in Umbilical, it warranted the need for high strength steel, ICSS-14-5PH[6]. Properties are given in Table-1.

Table 1: Properties of ICSS-14-5 PH Stainless steel [6]

Chemical Composition: (% weight)		
C:0.07 (Max)	Cr: 13.2-14.7	Ni: 5-8
S : 0.025 (Max)	Cu:1.2 – 2	Nb: 0.1-0.4
Mn : 1 (Max)	Mo:1.2-2	P: 0.035 (Max)
Si:0.6 (Max)	Fe: Balance	

Mechanical properties	
Ultimate Tensile Strength	930 MPa (Min)
Yield Strength	800 MPa (min)
Elongation	15% (min)
Young’s Modulus	209 GPa
Brinel Hardness	BHN 300 (min).

4.2 Preliminary Design

4.2.1. Estimation of torque

Axial load to be induced by the collet, Fa: 75 kN; Torque to be applied, T = K.d.Fa= 750 Nm

Where,
d: is nominal diameter of the lock nut,
K: is nut factor which defines the relationship which exists between applied torque and achieved preload in a given situation (for steel fasteners, nut factor is 0.238≈ 0.24 from standard tables)

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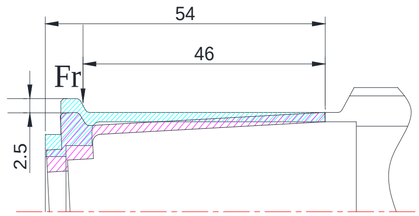

Fig.3. Deflection of collet beam

4.2.2. Load for deflection of collet beam [7]

Collet is deformed due to the radial force component acting on the segments. Using beam deflection equation for a cantilever beam (Refer Fig3) the load required to deform one collet is estimated

i.e. $W = \frac{3.E.I.\delta l}{l^3}$=43.5 N

Where,
W:load required to deforme one element of the collet,
δl: deflection required for releasing the lock= 2.5 mm
l: length of the beam= 46 mm (Cantilever length),
E: Modulus of Elasticity of the material = 2 x 10^5 N/mm^2.
I: Area Moment of Inertia.

$$I = I_1 - \left[\frac{1}{a(R^2-r^2)}\right]\left[\frac{2}{3}.(R^3-r^3).\sin a\right]^2 = 2.82\ mm^4$$

Where, $I_1 = \frac{a}{4}.(R^4-r^4)[1+\frac{\sin a.\cos a}{a}]$
For given collet, a = 11.25°,R = 18mm, r = 16.3mm.
Therefore, total load (P) required for radial collet deformation = W x n = 696 N
where n = 16 (number of collet beams)
Radial load available for collet deformation,
$F_r = F_a$. tan (25^0) = 35 kN, which has huge margin over required load.

4.2.3. Bending stress on collet beams [7],[8]

From the bending moment equation,
$\sigma_b = \frac{M.y}{I}$ = 603 N/mm^2
where,
σ_b :bending stress induced in collet beam,
M :bending moment = W.l = 2001 N mm
y : distance from neutral axis = 0.85 mm,
l:length of the beam= 46 mm (Refer Fig 3).
For selected material, factor of safety (FOS) is 1.33.

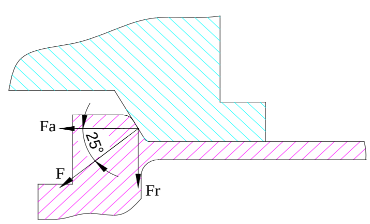

Fig.4 Collet loading pattern

4.2.4. Tensile stress on collet segment [7],[8]

The axial load to be induced on the collet is 75 kN and is shared by all 16 collet beams (Refer Fig4).
Thus, axial load induced on each segment,
F_a = 75000/16=4687.5 N, Area of a single collet beam, A = 9.03 mm^2.
Tensile stress on each collet = $\frac{Fa}{A}$= 519.1 N/mm^2
For selected material , factor of safety (FOS) is 1.54.

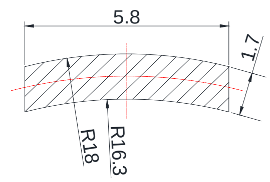

Fig.5 Cross section of collet beam

4.2.5. Collet piston release load

The release load needed to pull piston from collet,
F = µ . R = 5600 N
Where, F : release load, µ : friction factor for dry static friction = 0.16-0.17 (Piston was coated with a dry film lubricant MoS_2), R : F_r, normal force between contact surface (Refer Fig 5).

4.3 Finite Element Analysis

To verify the preliminary design and study the effect of variation in 'K', structural analysis was done through 'Ansys' software.

Case-1, T=750 Nm & K=0.15, simulating maximum load condition. Results revealed that plastic strain reached to 18% which was unsafe. Fig 6&7 show Von-Mises stress distribution and Equivalent Plastic strain on collet for case-1.

Case-2, T=750 Nm & K= 0.2, analysis showed that plastic strain is significantly reduced to 1.2% and minimum margin on yield strength was 0.12, which was acceptable. Fig.8 & 9 depict Von-Mises stress distribution and Equivalent Plastic strain on collet for case-2.

Case-3, T= 750 Nm & K= 0.24, analysis showed no plastic strain. The increased value of nut factor further aided in reducing plastic strain in collet thus ensuring better structural margins. In all cases, radial load developed was sufficintly high to deflect collet beam, essential for release.

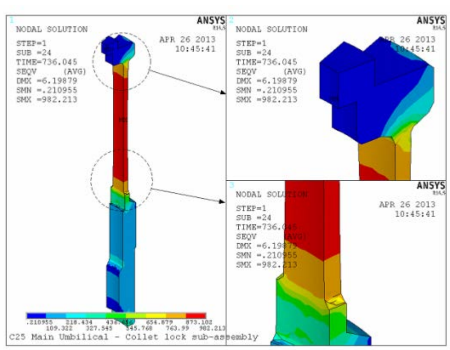

Fig.6 Von–Mises Stress Distribution (Case-1)

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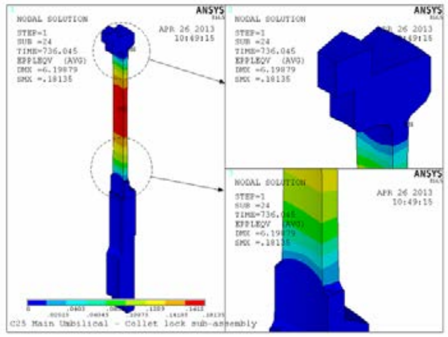

Fig 7: Equivalent Plastic Strain (Case-1)

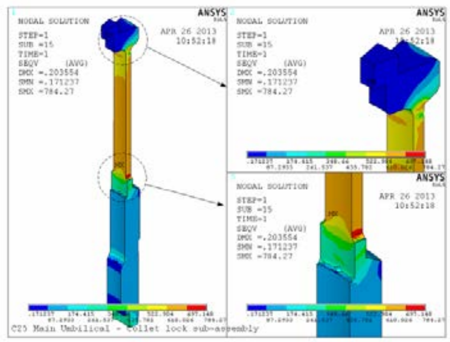

Fig 8: Von–Mises Stress Distribution (Case-2)

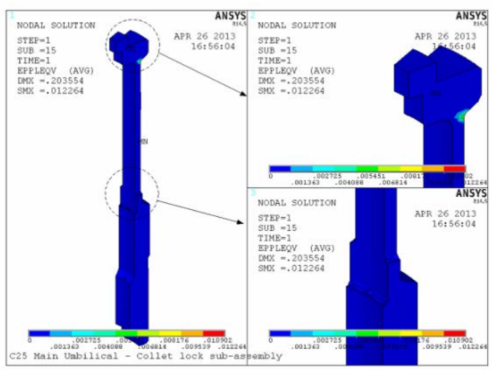

Fig 9: Equivalent Plastic Strain (Case-2)

5. Experimental Evaluation of Pre-Load

Extensive characterisation of collet lock was crucial to gain confidence in system. For a given thread size & torque, axial load induced depends on Nut factor (K). Nut Factor depends on friction in threads and contact surfaces. A test plan was devised to obtain K value & preload generated when torque is applied. Characterization of system demanded a load source capable of producing& measuring higher loads ($\geq$ 80kN). Calibrated Belleville disc stack was selected as it can take high loads with less deflection. The set-up [9] consisted of actual flight plate (FP) & ground plate-1 (GP-1) with collet lock S/A. GP-1 is part of GS & forms the part of collet joint upon mating with FS. Accordingly stack of 4 belleville discs in parallel was finalised and calibrated in Universal Testing Machine (UTM).

5.1 Test set-up

Collet lock was assembled into FP and Belleville stack was located between FP and GP-1. Lock nut was assembled and torqued gradually in steps with pre-calibrated wrench. High precision micrometer was used to measure gap between FP & GP-1 at discrete points. Measured gap was correlated to the “load vs compression” curve obtained earlier. Data of preload generated against torque given was plotted for different sets of collets. Fig.10 shows test setup. In the first trial, axial load induced was much lower than anticipiated and also the bearing surfaces of collet and locknut were damaged. Problem was identified as galling [10], a phenomenon of microscopic material transfer between surfaces compressed with high loads due to combination of friction and adhesion.

Galling is more prevalent in low hardness material and gets aggravated in absence of lubrication.As per ASTM standard G40 [11], its a form of surface damage arising between sliding solids, distinguished by microscopic, usually localized, roughening and creation of protrusions above the original surface. Major fraction of torque was consumed in overcoming friction thus reducing axial load induced. Fig 11 shows "Torque vs Axial load plot for galling". John H Bickford [12] gives an insight into the need, working principle, applications, selection and types of thread lubricants; also its effect on nut factor. Works published by E.Hemmati V [13] and Richard T. Barrett[14] speak about the effect of lubrication of threads on the clamping value which was studied for both conditions (dry and lubricated threads). Based on various literature studies & trials, the problem was overcome by two means. Firstly introducing a washer made of Aluminium bronze (C-62300)[15] between lock nut & collet and second was application of a thread lubricant named Fluorogrease/ Cryogel (CSNM-22) on threads and butting faces. CSNM-22 is a per-Fluoro-polyether oil with viscosity of 5000^{+1000} poise at 30^{o}C, used as a lubricant in sliding & spherical joints in cryogenic applications. The Aluminium bronze washer solved the problem of galling & in combination with Cryogel reduced 'K' to a desired level (≈ 0.2). Further experiments were carried out on 6 number of hardware's and resultswere satisfactory.

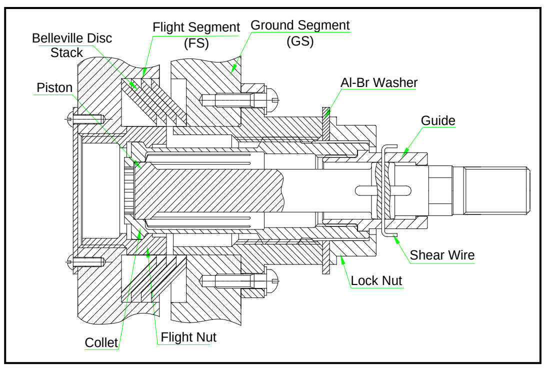

Fig.10. Test set up with Belleville disc pack

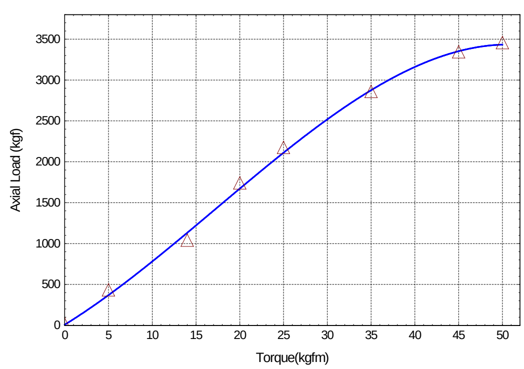

Fig 11: "Torque vs Axial Load" plot for galling

Owing to reduced 'K',torque value was reset at $650^{\pm 20}$ Nm to achieve preload of 75 kN. Fig 12 shows test result for 650 Nm torque.

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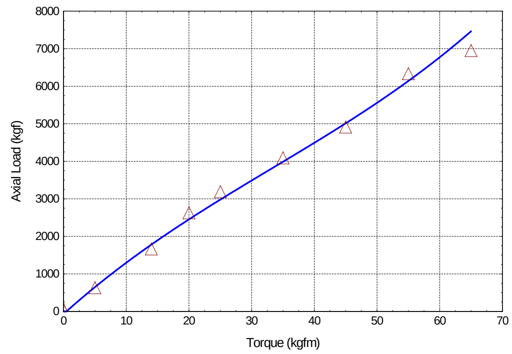

Fig 12: "Torque vs Axial Load" plot for 650 Nm Torque

5.1 Evaluation of Collet Piston Release Load

Release load required depends on radial load (Fr) and friction factor between piston and collet. Radial load on piston is a derivative of interface geometry & preload. Release load dictates the size/envelope of pyro puller and secondary release mechanism, hence optimisation of load is a must.

The release tests were carried out in UTM. Test set up involved FP & GP-1 clamped together by collet lock with a torque of 650Nm. FP was rigidly fixed to UTM base and piston was connected to moving bench of UTM. UTM had maximum tensile capacity of 100 kN and least count of 1N with maximum speed of 510mm/min. Results exhibited an average release load of 5,500 N with load rising smoothly & sharply to the peak value. Fig. 13 shows result for this kind of loading.

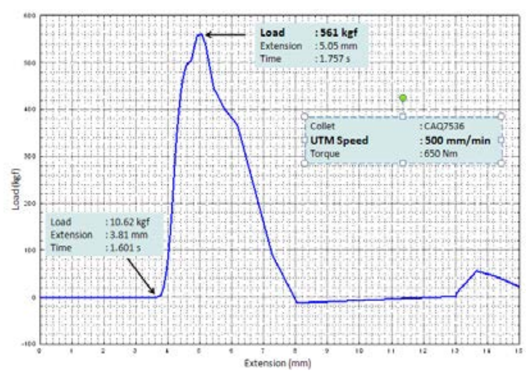

Fig 13: "Pull Load vs Stroke" plot for 510 mm/min

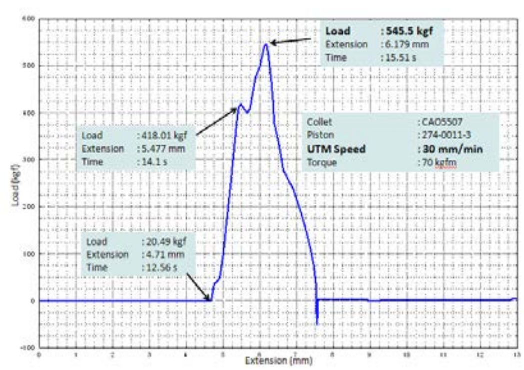

Fig 14: "Pull Load vs Stroke" plot for 30 mm/min

Test plan was extended to validate unforeseen scenarios like i) low speed release and ii) incremental loading. Low speed release test was done at 30mm/min speed and profile plot had a distinct peak (dent) before peak load. First peak averaged at 4,000 N and was attributed to cutting of shear wire. Second peak (release load) averaged at 5,200 N. Fig.14 is one example of Load vs time plot of pull test done at 30mm/min. For gradual incremental load case, initial load was kept significantly below the average pull load (5,500N). Load was increased from 3,200N in steps of 50N with 6 minutes hold for each step. On the whole the peak load observed in this case was significantly lower than first two modes (4,200N). This was attributed to inherent vibrations in UTM assisting in release. Fig.15 depicts typical plot of this gradual loading & Fig.16 shows close-up view of the actual loading region. Test results are given in Table 3.

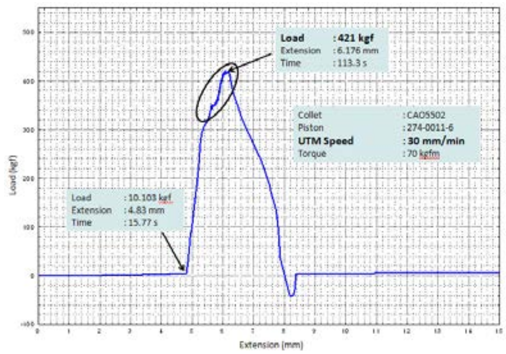

Fig 15: "Pull Load vs Stroke" plot for gradual loading

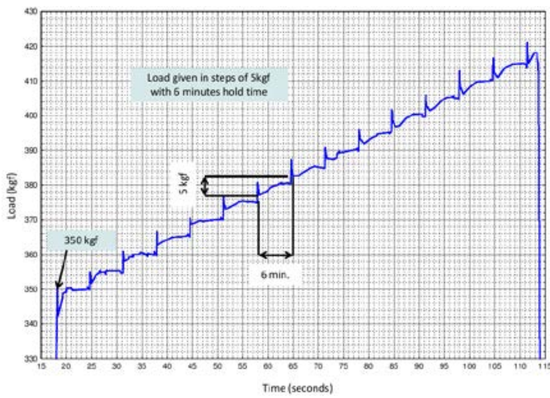

Fig 16: Close up view of gradual loading region

Table.3 Summary of axial & release loads

Sl No	Test	Axial Load Induced (kN)	Release Load (N)
1	Collet Assembly-1	75.2	5610
2	Collet Assembly-2	76.2	5770
3	Collet Assembly-3	72.2	5380
4	Collet Assembly-4	76.5	5450
5	Collet Assembly-5	72	5230
6	Collet Assembly-6	73.4	5100
7	Collet Assembly-7	74.2	5280
8	Collet Assembly-8	72.9	5190
9	Collet Assembly-9	75.4	5710
10	Collet Assembly-10	77.5	5870

Thus the collet lock was satisfactorily qualified & proven for higher load margin. Finalised torque value is $650^{\pm 20}$ Nm which induces axialload of 75 kN and needs release load of $5.5^{\pm 0.5}$ kN.

5. Conclusion

The paper has presented in detail characterization studies carried out on a heavy duty collet lock of cryogenic umbilicals. Paper narrates test plan devised and executed towards development & qualification of a reliable collet lock mechanism. The content is sequentially arranged beginning with requirements & significance of the test, followed by brief introduction of umbilical system, collet lock design criteria, test article & test set up. FE analysis conducted on collet is also touched upon. The introduction is succeeded by exhaustive narration of characterization and qualification tests conducted to prove the collet lock mechanism. Problems faced during the characterization and solutions implemented are also brought out. As for any launch vehicle system, elaborate test plan was envisaged simulating actual working conditions to its best. The series of release tests (10 Nos.), analysis after each test and implementing changes enabled to characterize and prove a reliable collet lock mechanism. After successful characterization, the collet lock sub assembly was inducted in Cryogenic Umbilicals and as part of system level qualification had satisfactorily performed during locking and separation (both by primary & secondary mode, 10 Tests). These tests and analyses led to successful induction of Cryogenic Umbilical systems in ISROs launch vehicles and performed flawless in its maiden flight, both with respect to holding & smooth separation.

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