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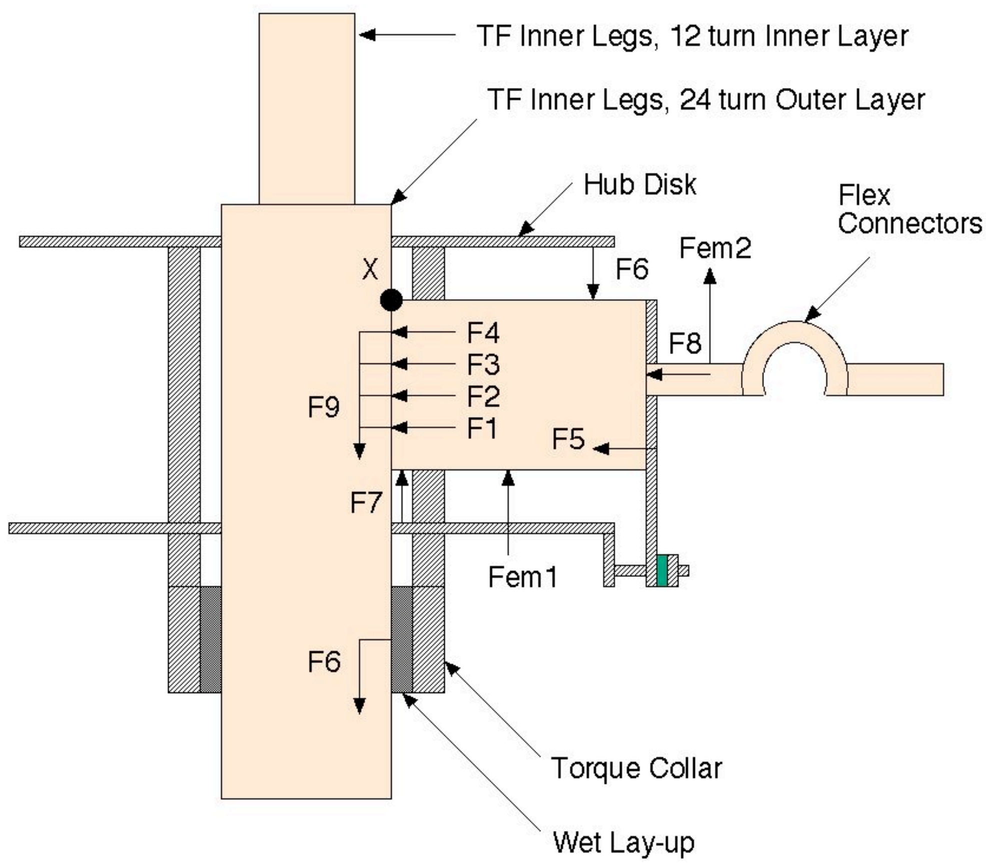
TO: DISTRIBUTION
FROM: C NEUMEYER
SUBJECT: TF FLAG JOINT FORCES AND LOAD PATHS

This memo provides rough estimates of in-plane forces on the TF flags and evaluates the various load paths. It is intended to provide guidance for the initial sizing of the various mechanical components of the joint. Finite element analysis presently underway will provide more accurate information for finalizing the design.

Forces and Load Paths

A schematic of a inner tier flag associated with an outer layer turn is shown in the following figure.



A description of the forces and load paths is as follows:

F_{em1}: Vertical EM force generated on the flag. Assumed to include JxB_t contribution from both flag halves, along with attractive force between the flags in the two tiers. Inner flag half assumed to carry 3x current of outer flag half. Force on each conductor assumed equal to $Jx(B_{self}/2 + B_{ext})$. Here B_{self} is the self-field and B_{ext} is the field produced by the other conductors, including those from both the 24 and 12 turn tiers. The effective radius at which the force is applied is that where the field is at its average value along the length in question.

F_{em2}: Vertical EM force generated on linkage between flags and outer legs, consisting of solid connectors on either side of a flexible link. Total force across link is shared between inner and outer leg assemblies. Here it is assumed that force generated up to midpoint of omega in flexible link is applied to inner leg assembly. Distance from flag end to midpoint of omega is assumed to be 6". Again, forces are based on $Jx(B_{self}/2 + B_{ext})$, and the effective radius at which the force is applied is that where the field is at its average value along the length in question.

F1, F2, F3, F4: These are the inward radial forces generated by the tension in the thru-bolts.

F5: This is an additional inward radial force generated by a proposed jack-screw arrangement which acts between the flag end and the hub disk.

F6: This is a downward force provided by the hub assembly via the flag insulation, shim, hub disk, torque collar, wet lay-up, and TF ground and turn insulation, all in series. It resists the vertical forces on the flag as well as rotation of the flag about point X.

F7: This is an upward force provided by the hub assembly which resists rotation of the flag about point X.

F8: This is an inward radial force which resists rotation of the flag about point X. It acts through the flexible link.

F9: This is a downward vertical force which resists the vertical EM forces on the flag via the frictional connection between the flag and the inner leg conductor as well as shear of the bolts and/or pins connected across the joint.

The EM forces on the flags and links at 6kG (71.2kA/turn) are given in the following table.

Summary of Forces and Moments at 6kG

	$F_{vertical}$ (lbs)	dR from point of application to flag inboard edge (in)	Moment w.r.t. point X (in-lbs)
Inner Tier Flag	7380	4.3	31719
Inner Tier Link	1855	13.8	25652
Outer Tier Flag	1845	4.3	7930
Outer Tier Link	464	13.8	6413
Total from All Turns	249324		

Clearly the forces on the inner tier (associated with the 24 turn outer layer) are much higher than the outer tier.

Reaction of Applied Moments

Because of the relatively high elasticity of the load paths associated with F6, F7, and F8 they are discounted in the following discussion. This is a worst case scenario for the bolted joint load path.

The applied moment on the flag is equal to $F_{em1}*dR_{em1}+F_{em2}*dR_{em2}$. Assuming that F6, F7, and F8 do not react against this moment it must be taken by F1, F2, F3, F4, and F5.

Let F5 be an input variable. Assume that the relative values of F1, F2, F3, and F4 vary in proportion to their vertical distance z to point X. This is based on the idea that, as the flag rotates through an angle θ about point X, the elastic deformation of the bolts will be ~ zθ, □□□ the associated force will be in proportion to z.

With these assumptions the values of the thru-bolt forces required to counteract the applied moment can be estimated. Then the total tension on the bolts is equal to the preload plus the additional force required to react the moment.

The preload must be chosen such that, under full EM load, adequate contact pressure is maintained. Given this requirement, the required thru-bolt preload and peak force in the highest stressed bolt (the one which supplies F1) can be estimated based on the assumption that the radial force acting against the preload is equal to the applied moment divided by the half height of the flag.

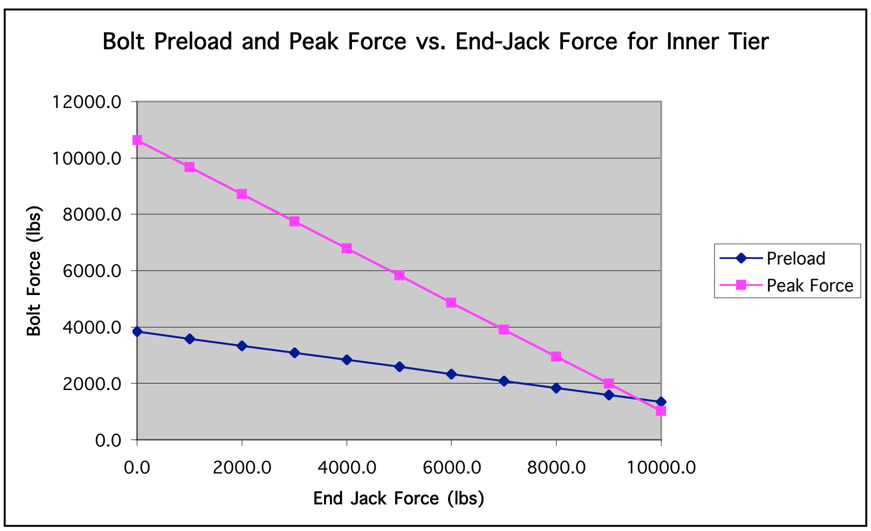
The following table shows the forces and stresses corresponding to the case where an average contact force of 10000 lbs, equivalent to a contact pressure of approximately

1000/5in^2=2ksi, is maintained under all conditions. An F5 force of 5000 lbs applied at a distance of 6" below point X. For this case the required bolt preload is 2584 lbs.

Inner Tier Forces and Reactions with 5000 lb. End-jack

∑Applied Moments	57371.7	in-lbs
dZF1	4.750	in
dZF2	3.500	in
dZF3	2.125	in
dZF4	0.875	in
dZF5	6.000	in
F5	5000.0	lbs
F1	3242.8	lbs
F2	2389.4	lbs
F3	1450.7	lbs
F4	597.4	lbs
Bolt Preload	2584.2	lbs
Ftot1	5827.0	lbs
Ftot2	4973.7	lbs
Ftot3	4035.0	lbs
Ftot4	3181.6	lbs
∑Fr	10000.0	lbs

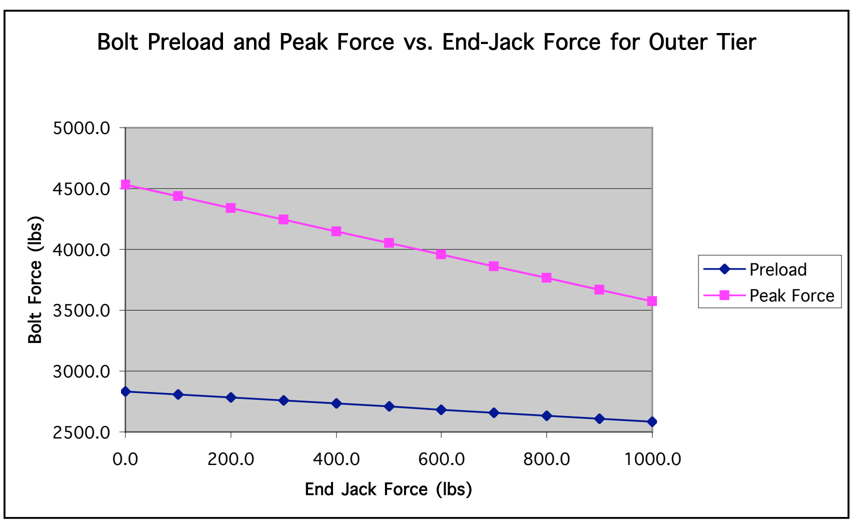
The following curve shows the required bolt preload, and the peak force (in bolt 1) as a function of end-jack force F5.



The following table and curve show the results for the outer tier which experiences considerably less force.

Outer Tier Forces and Reactions with 0 lb. End-jack

Fem1	1844.9	lbs
dRem1	4.3	in
Fem2	463.7	lbs
dRem2	13.8	in
∑Applied Moments	14342.9	in-lbs
F5	0.0	lbs
F1	1699.2	lbs
F2	1252.1	lbs
F3	760.2	lbs
F4	313.0	lbs
∑Reaction Moments	14342.9	in-lbs
Bolt Preload	2833.6	lbs
Ftot1	4532.8	lbs
Ftot2	4085.6	lbs
Ftot3	3593.7	lbs
Ftot4	3146.6	lbs
∑Fr	10000.0	lbs



Reaction of Vertical Forces

Two load paths are available to react the vertical loads. The first (F9) is via shear at the interface between the flag and the inner leg assembly, and the second (F6) is via the shims/hub assembly/torque collar/wet lay-up/ground/turn insulation. The former is much stiffer than the latter, so it probably takes most of the load.

The maximum force on a flag occurs on the inner tier, and is the sum of the forces generated on the flag and on the link to the outer leg, equal to 7379 + 1855= 9234 lbs. Assuming a contact pressure of order 10000 lbs, a coefficient of friction of 0.9234 would be required to react this force, which is unrealistic. Therefore if most of the load has to pass through the joint it is clear that additional shear components (shoulder bolts, keys, etc.) are necessary.

The torque collar will end up carrying some fraction of the total load of 249324 lbs. Additional stress is imposed on the collar wet lay-up from the torsional load due to J_{TF} x B_{rOH}. The following table estimates the shear stress on the wet lay-up system from the combined vertical and torsional loads, assuming that the full fraction of the vertical load appears on the collar.

Worst Case Forces and Reactions on Collar

Collar Height	3.25	in
Inner Leg Groundwall Outer Radius	3.96	in
Circumference	24.88	in
Area	80.86	in^2
Vertical Force	249324.7	lbs
Torque	100000.0	N-m/m
	8255	N-m
	6088.3	ft-lbs
	73060.0	in-lbs
Torsional Force	22480.0	lbs
Effective Force	250336.1	lbs
Average Shear Stress	3095.9	psi

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