APR1400 Flywheel Integrity Analysis

Presented by

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APR1400-A-M-EC-14001-NP
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KEPCO

KHNP

APR1400 Flywheel Integrity Analysis

Acceptance Criteria

Acceptance Criteria per Design Specification

1. At standstill and normal operating speed, total stress < 1/3 S_y.
2. At design overspeed = 125% normal speed, total stress < 2/3 S_y.
3. At joint release speed, total stress < lesser of ½ S_u and 2/3 S_y.
   Joint release speed ≥ 150% normal speed

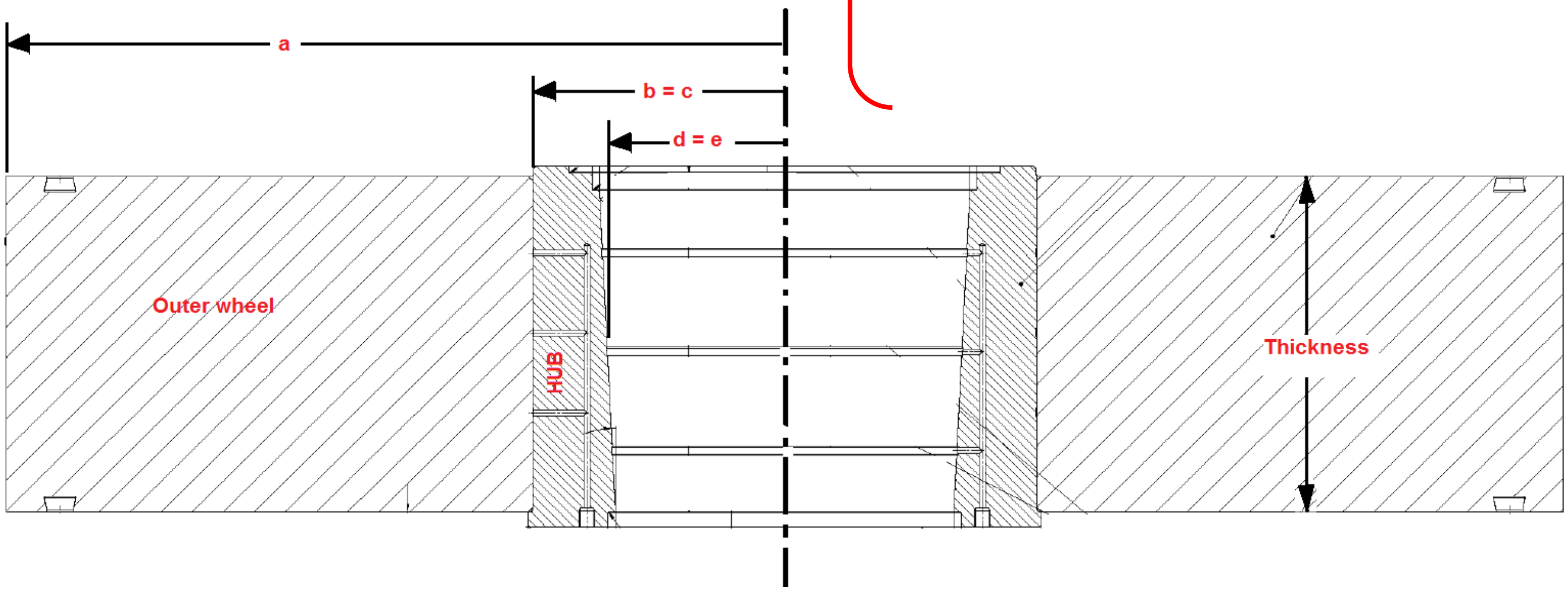
Acceptance Criteria per Reg. Guide 1.14

4. Flywheel should be designed to withstand normal conditions, transients, LOCA and SSE.
5. Critical speed for ductile fracture should be predicted.
6. Critical speed for non-ductile fracture should be predicted.
7. The normal speed < ½ of the lowest critical speeds.
8. The LOCA overspeed < the lowest critical speeds.
9. The critical speed for excessive deformation should be predicted.

APR1400 Flywheel Integrity Analysis

Flywheel Assembly Dimension Sketch

a, c



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Shrink Fit Stress and Radial Displacement

Outer Wheel Displacement:

$\Delta b = (Pb/E)[(a^2 + b^2)/(a^2 - b^2) + \nu]$ Equation 1

- a= outside radius of wheel
- b = inside radius of wheel
- P = contact pressure between outer wheel and hub
- E = Young's modulus
- ν = Poisson ratio

Radial Stress:

$Sr = -Pb^2(a^2 - r^2)/[r^2 (a^2 - b^2)]$ Equation 2

- P = contact pressure on inner radius of wheel
- r = distance from center of wheel

Tangential Stress:

$St = Pb^2 (a^2 + r^2)/[r^2 (a^2 - b^2)]$ Equation 3

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Shrink Fit Stress and Radial Displacement

Hub Displacement:

$\Delta c = -(Pc/E)[(c^2 + d^2)/(c^2 - d^2) - \nu]$ Equation 4

c = outside radius of hub

d = averaged inside radius of hub

Radial Stress:

$Sr = -Pc^2(r^2 - d^2)/[r^2(c^2 - d^2)]$ Equation 5

P = contact pressure on outer radius of hub

r = distance from center of wheel

Tangential Stress:

$St = -Pc^2 (d^2 + r^2)/[r^2 (c^2 - d^2)]$ Equation 6

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Rotation Stress and Radial Displacement

Outer Wheel Displacement:

$\Delta b = (1/4)(\rho/g)\omega^2(b/E)[(3 + \nu)a^2 + (1 - \nu)b^2]$ Equation 7

ρ = density

g = gravitational acceleration

ω = rotational speed (radian/sec)

Hub Displacement:

$\Delta c = (1/4)(\rho/g)\omega^2(c/E)[(1 - \nu)c^2 + (3 + \nu)d^2]$ Equation 8

Tangential and Radial Stress due to rotation:

$St = (1/8)(\rho/g)\omega^2[(3 + \nu)(a^2 + d^2 + a^2d^2/r^2) - (1 + 3\nu)r^2]$ Equation 9

$Sr = (1/8)(3 + v)(\rho/g)\omega^2[a^2 + d^2 - (a^2d^2/r^2) - r^2]$ Equation 10

r = radial location of the stress

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Stress Intensity Factor of Assumed Crack

4th order through-wall tangential stress profile

$$St = S0 + S1(x/t) + S2(x/t)^2 + S3(x/t)^3 + S4(x/t)^4 \quad \text{Equation 11}$$

Axial crack in a cylinder Per API 579-1/ASME FFS-1

$$K_I = [G0S0 + G1S1(a/t) + G2S2(a/t)^2 + G3S3(a/t)^3 + G4S4(a/t)^4](\pi a)^{1/2} \quad \text{Equation 12}$$

a = radial dimension of assumed crack
t = distance between inner and outer radii of wheel
x = distance from cracked edge
G = Coefficients from API 579-1/ASME FFS-1, Table C.10.

a, c

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Flywheel Material

Normal Operating T = 49°C = 120°F

E = 204,000 N/mm^2 = 29,587,956 psi.

Nil Ductility Temperature, NDT $\leq$ 10°F

Minimum K_{IC} = 5,250 $N/mm^{3/2}$ = 150 $ksi\text{-}in^{1/2}$

Density = 7,850 kg/m^3 = 0.283 lbs/in^3

Minimum Su = 800 N/mm2 = 116,000 psi

Assume Sy = 800 N/mm^2 = 116,000 psi.

The actual material minimum Sy must be confirmed by the manufacturer in order for this calculation to be applicable to the APR1400 flywheel. Actual Su would be higher with Sy = 116,000 psi. Su=116,000 psi is conservatively used for analysis.

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Shrink Fit Requirement

The required shrink fit to achieve the joint release speed is at least 1800 rpm (150% normal) is calculated.

However, the more stringent minimum shrink fit values from Siemen's calculation was used for conservatism:

a, c

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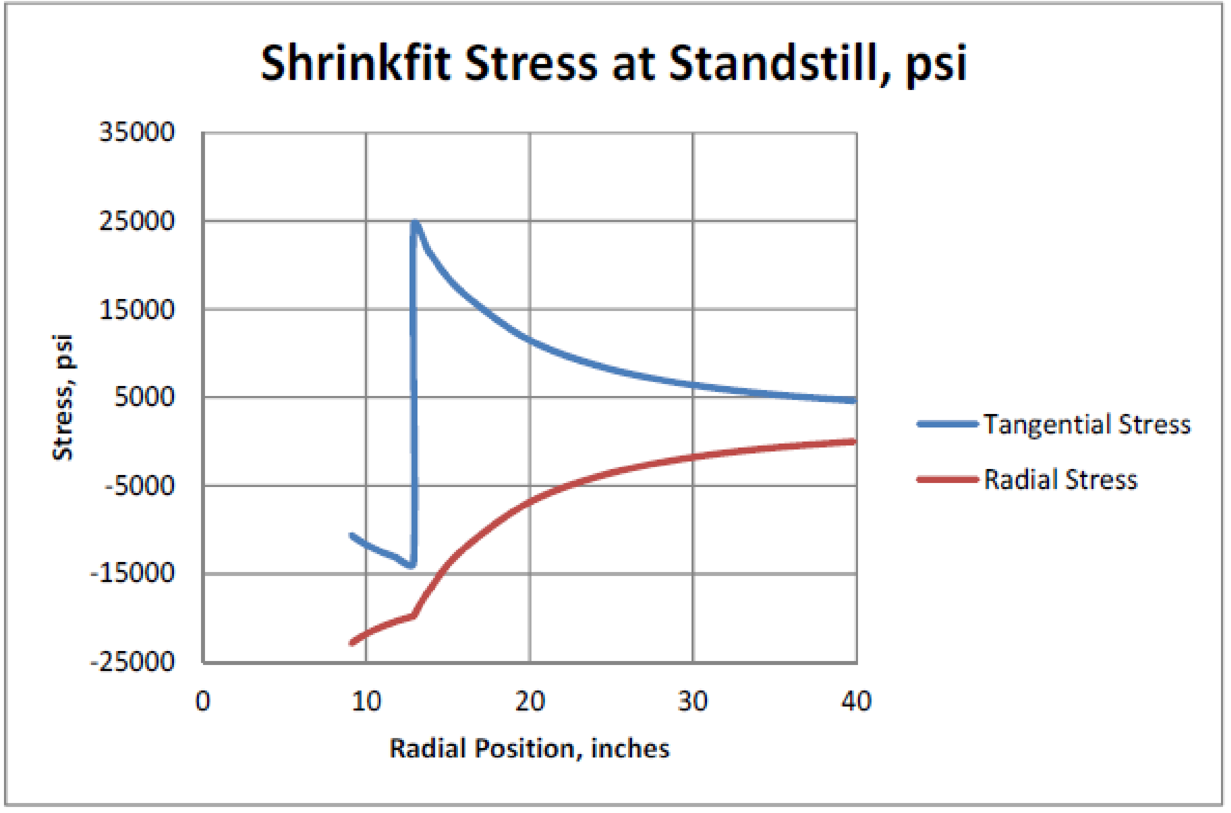
Shrink Fit Stress at Stand Still



The radial contact stress between the hub and the outer wheel is -19,789 psi.

The peak stress at the inside radius of the outer wheel is 24,418 psi.

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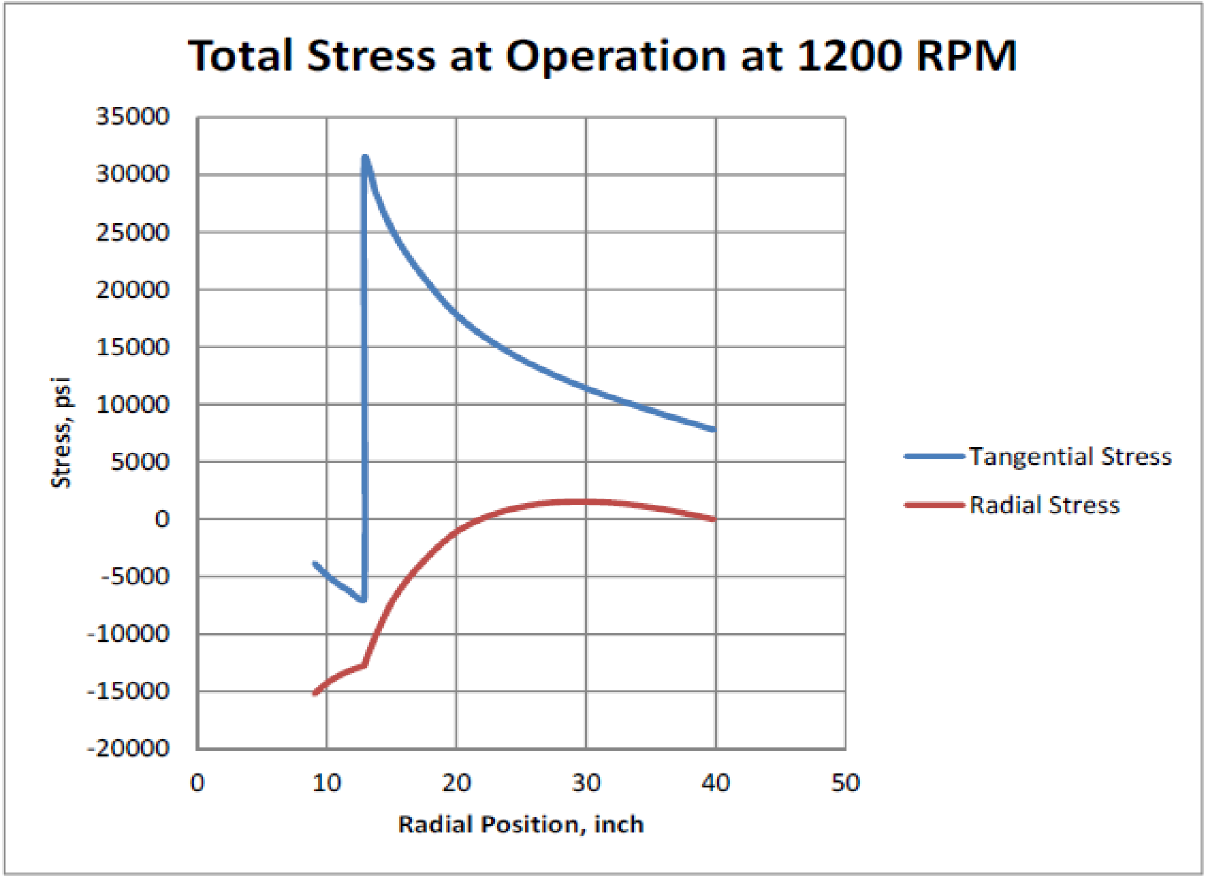
Total Stress at Normal Operation, 1,200 rpm



The radial contact stress computed between the hub and the outer wheel is -12,770 psi.

The peak stress computed at the inside radius of the outer wheel is 31,240 psi.

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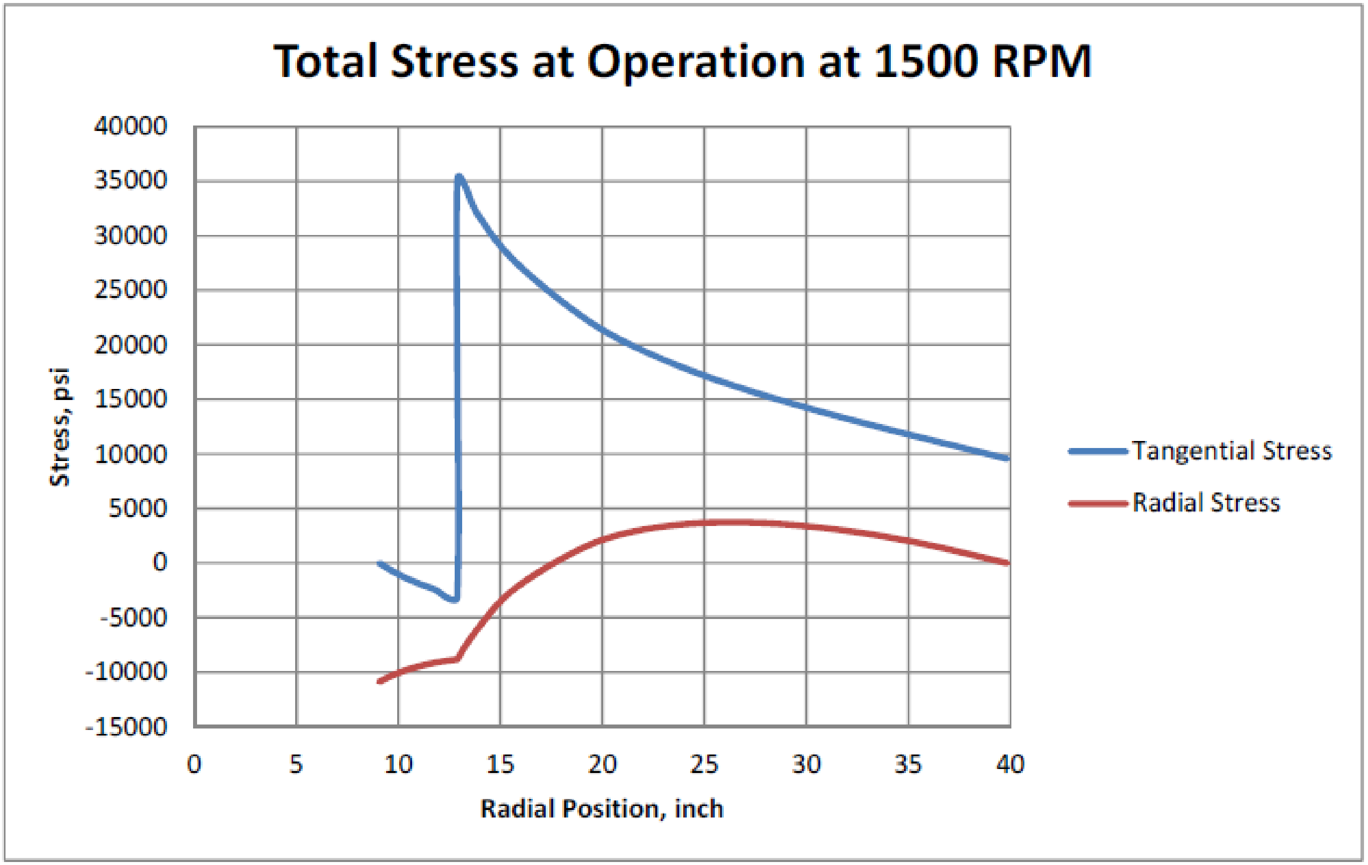
Total Stress at LOCA Overspeed, 1,500 rpm



The radial contact stress between the hub and the outer wheel is -8,722 psi.

The peak stress at the inside radius of the outer wheel is 35,078 psi.

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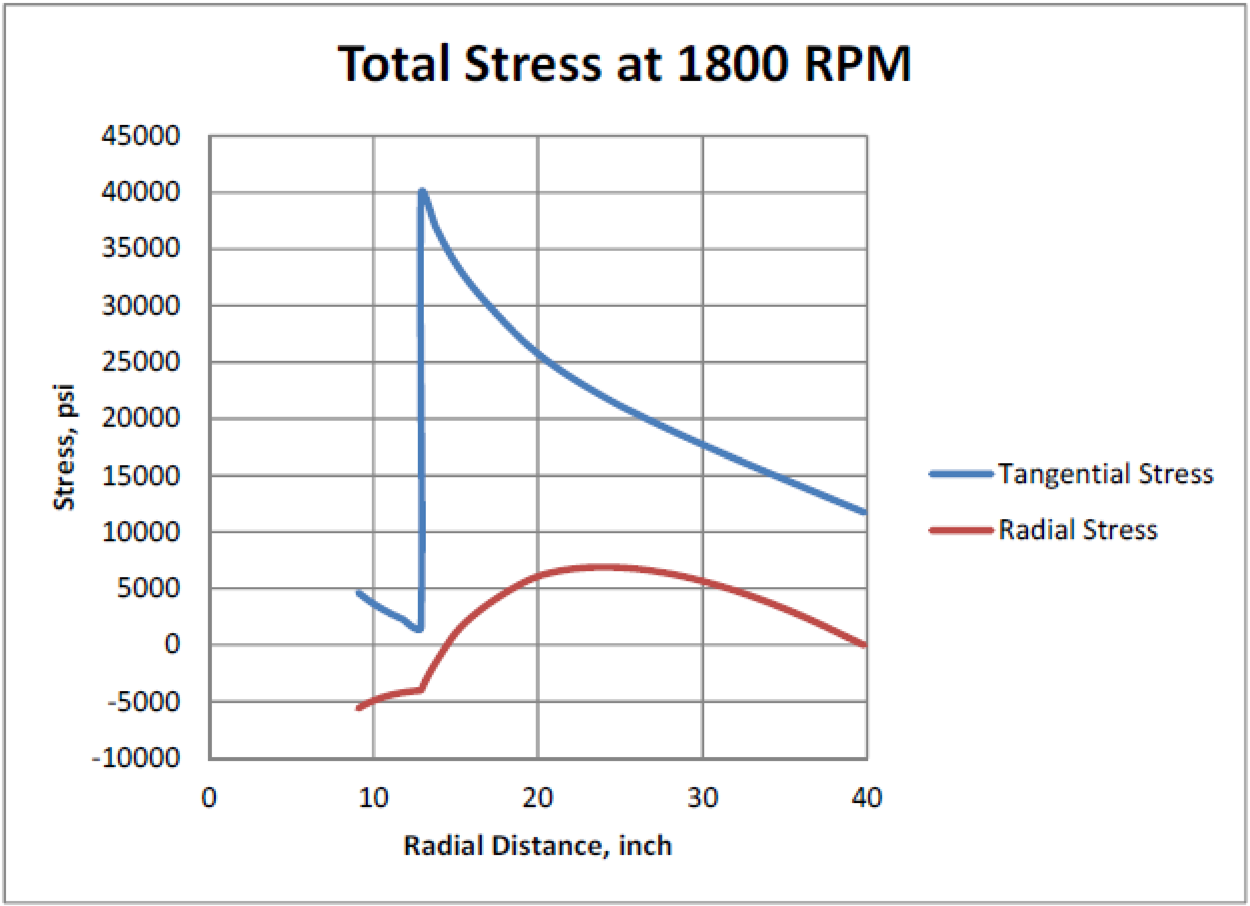
Total Stress at 150% Normal Speed, 1,800 rpm



The radial contact stress between the hub and the outer wheel is -3,997 psi.

The peak stress at the inside radius of the outer wheel is 39,768 psi.

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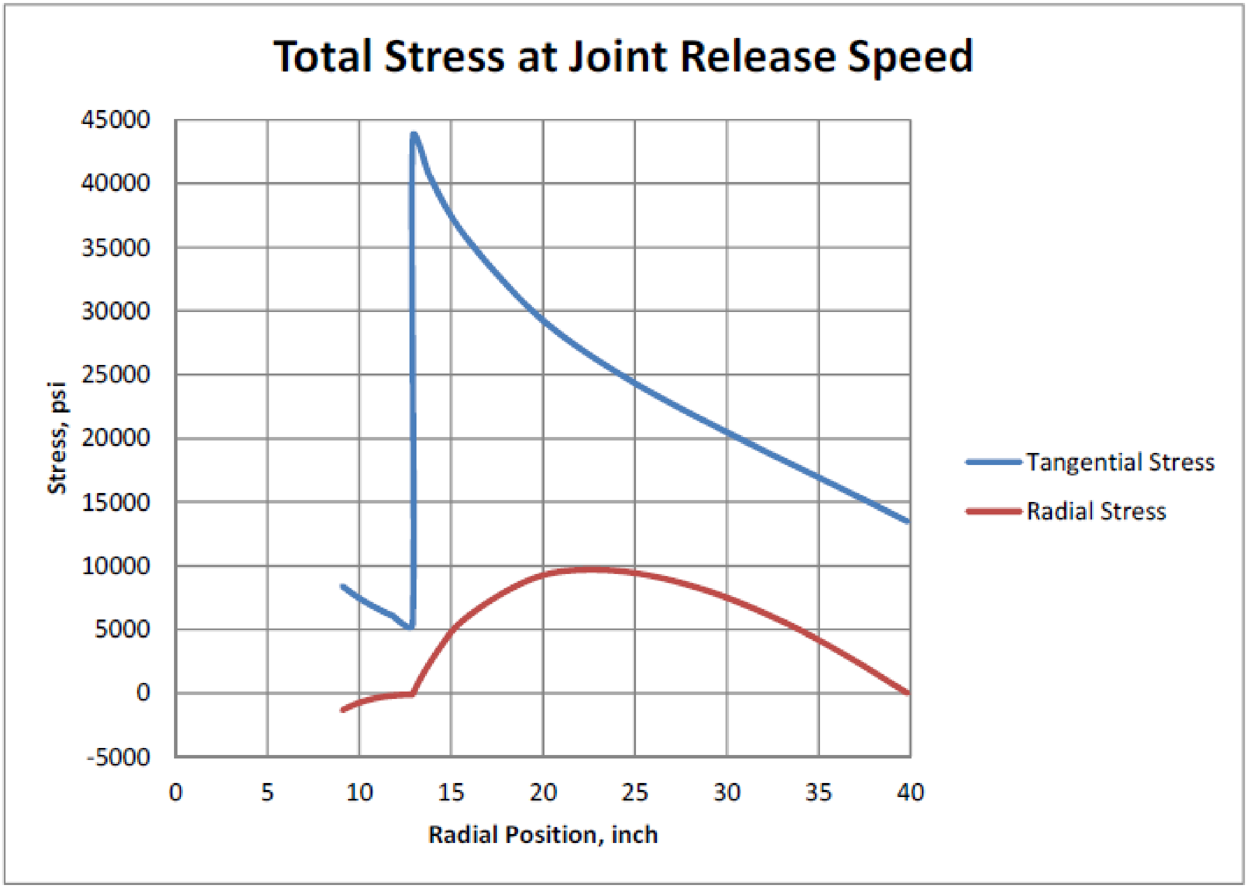
Total Stress at Joint Release, 2,010 rpm



The radial contact stress between the hub and the outer wheel is zero.

The peak stress at the inside radius of the outer wheel is 43,559 psi.

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Design Specification Criteria and Results

Criterion 1: At standstill and normal operating speed, total stress < 1/3 S_y.

Total stress = 38,674 psi < 38,677 psi = 1/3 Sy

Criterion 2: At design overspeed 1500 rpm (125% normal speed), total stress < 2/3 Sy.

Total stress = 40,156 psi < 77,353 psi = 2/3 Sy

Criterion 3: At joint release speed of 2010 rpm, total stress < lesser of ½ Su and 2/3 Sy.

Total stress = 43,599 psi < 58,015 psi = ½ Su

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RG 1.14 Criteria and Results

Criterion 4: Flywheel should be designed to withstand normal conditions, transients, LOCA and SSE.

- Design transients have insignificant effect on the flywheel.
- Normal condition and LOCA are addressed in Criteria 6 and 7.
- Assuming μ = 0.2, shrink fit $F_{friction}$ = 82.3 x deadweight (1g). It is significantly above the seismic design requirement. Criterion 4 is met

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RG 1.14 Criteria and Results

Criterion 5: Predict critical speed for ductile fracture.

- Per ASME III, F-1330, ductile fracture stress = 0.7Su.
- Separation speed = 2,010 rpm, Stress = 43,599 psi.
- No shrink fit ⇨ stress scales as the square of rotation speed. Stress = 0.7Su = 81,200 psi ⇨ Speed = 2,744 rpm

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RG 1.14 Criteria and Results

Criterion 6: Predict critical speed for non-ductile fracture.

- Through-wall tangential stress profile are fitted with a 4th order polynomial and K_I profiles are calculated for:
  - Standstill
  - Normal (1200 rpm)
  - LOCA overspeed (125% normal = 1500 rpm)
  - Shrink Fit requirement (150% normal = 1800 rpm)
  - Joint Separation (2010 rpm)
- Assume crack depth = 0.5 inch

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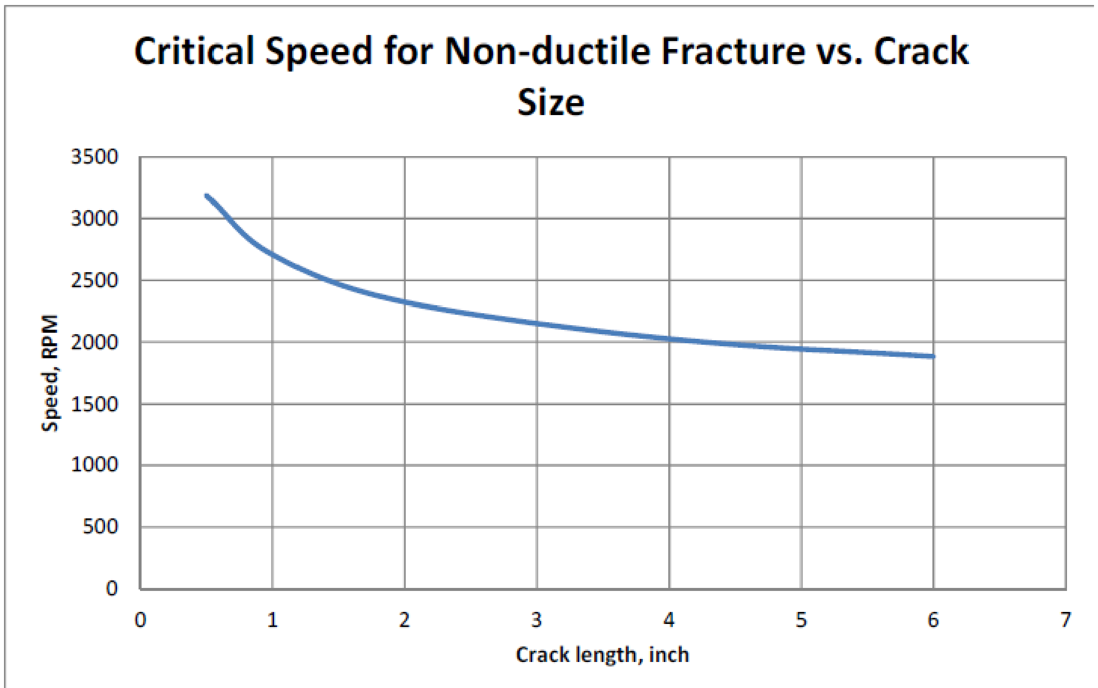
RG 1.14 Criteria and Results

Criterion 6: Predict critical speed for non-ductile fracture.

- Assume a crack length a = 0.5 inch, critical speed = 3,187 rpm



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RG 1.14 Criteria and Results

Criterion 7: Normal speed < ½ lowest critical speed.

Critical Conditions	Speed (rpm)	Normal Operation Speed/Critical Speed Ratio	Critical Speed/Joint Separation Speed Ratio
Ductile Fracture	2,744	0.44< 0.5 Per Criterion 7	1.37
Non-ductile Fracture	3,187	0.38< 0.5 Per Criterion 7	1.59
Excessive Deformation	3,280	0.36< 0.5 Per Criterion 7	1.63

Note: Since critical speeds > separation speed of 2010 rpm, these critical speeds are hypothetical and could not occur in real life..

Criterion 8: The LOCA Overspeed < the lowest critical speed.

- LOCA Overspeed = 1500 rpm < all critical speeds above

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RG 1.14 Criteria and Results

Criterion 9:

Predict the critical speed for excessive deformation.

- Excessive deformation can be conservatively defined as total stress = Sy.
- Separation speed = 2,010 rpm, with 43,559 psi.
  At Sy = 116,000 psi, the hypothetical speed = 3,280 rpm.
- This will not occur because the shrink fit will separate at 2,010 rpm. Therefore, the excessive deformation criterion is satisfied.

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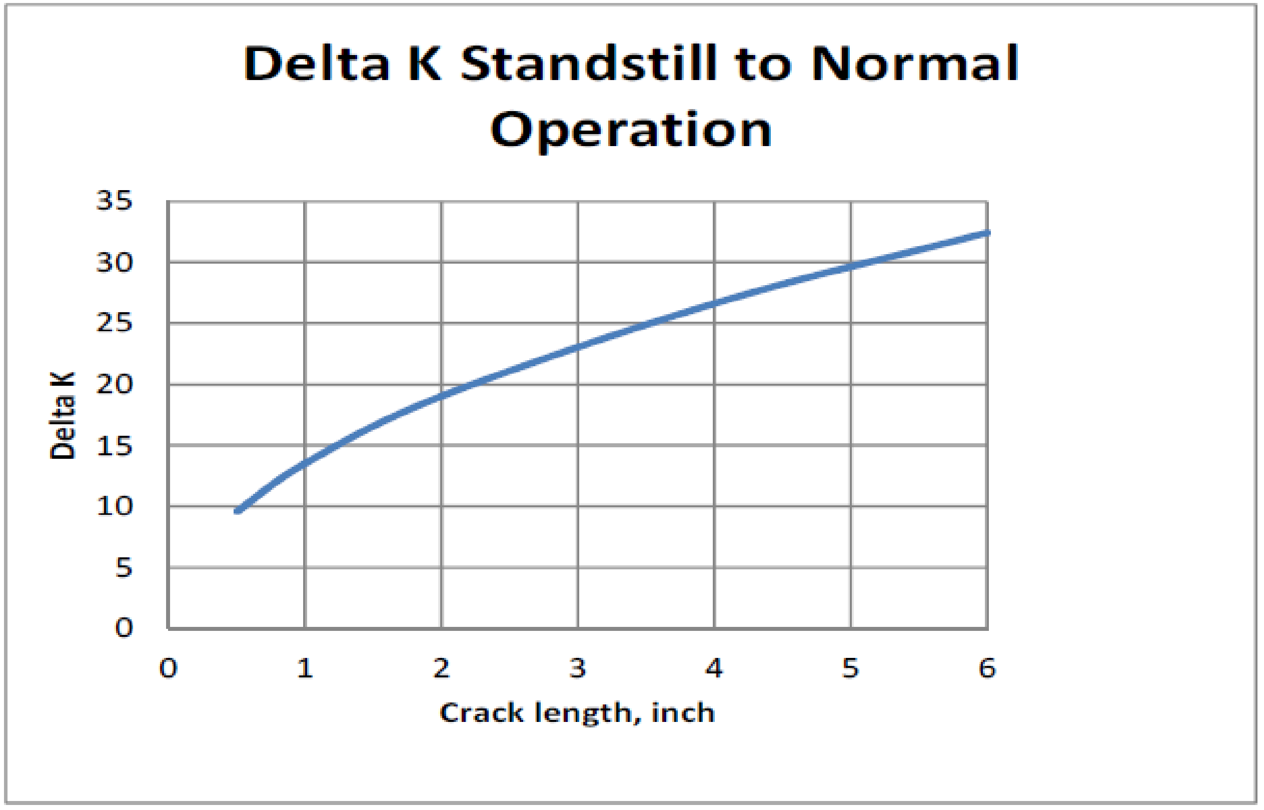
Fatigue Crack Growth

Cycle = 6,000 from standstill to normal (1200pm)



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Fatigue Crack Growth

Growth rate per ASME Section XI Appendix A 4300

$$da/dn = C_0 (\Delta K_I)^n$$

$$C_0 = 1.99 \times 10^{-10} S$$

$$S = 25.72 \times (2.88-R)^{-3.07}$$

$$n = -3.07$$

$$R = K_{Imin}/K_{Imax}$$

A 0.5 inch crack grows to 0.5032 inch in 6,000 cycles. Fatigue crack growth is negligible.

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Conclusions

- The APR1400 flywheel material has increased yield strength and ultimate strength through improved manufacturing process, although flywheel material combination remains the same as before.
- APR1400 RCP flywheel integrity analysis results show that all applicable criteria per design specification and regulatory guidance are met.

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Questions