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PREDICTION OF STRESS CONCENTRATION EFFECT UNDER THERMAL AND DYNAMIC LOADS ON A HIGH PRESSURE TURBINE ROTOR

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Abstract

Geometric discontinuities cause a large variation of stress and produce a significant increase in stress. The high stress due to the variation of geometry is called as ‘stress concentration’. This will increase when the loads are further applied. There are many investigators who have studied the stress distribution around the notches, grooves, and other irregularities of various machine components. This paper analyses the effects of thermal and fatigue load on a steam turbine rotor under the operating conditions. Stresses due to thermal and dynamic loads of High Pressure Steam Turbine Rotor of 210MW power station are found in two stages. A source code is developed for calculating the nominal stress at each section of HPT rotor. Maximum stress is obtained using FEA at the corresponding section. Thermal and Fatigue Stress Concentration Factors at each section are calculated. It is observed that the SCF due to the combined effect of thermal and dynamic loads at the temperatures beyond 540^0C is exceeding the safe limits.

Keywords: Stress Concentration Factors, HPT Rotor, Thermal and dynamic loads.

1. Introduction

G.E. Peterson [1] has done significant research on stress concentration of various machine components. Neuber [2] had done exhaustive research on stress concentration factors for extreme thin components. Heteny I. and Lin[3] developed charts for stress concentration factors for notches with flat bottoms. Stress Concentration Factors K_t for opposite U-shaped notches in a finite-width thin beam element are given in the charts by Froch[4]. J.N.Goodier and P.G.Hodge[5] have paid efforts on stress concentration of irregular shapes. For torsion, the membrane analogy was used by Pilkey and Wunderlic [6]. Isida [7] determined stress concentration factors for a thin beam element with opposite semicircular notches. The stress concentration factors K_t for flat-bottom notches in a shaft of circular cross section under tension were given in the charts by Noda [8]. S.J.Hardy and M.K.Pipelzadeh[9] have used the finite element method to obtain stress concentration factor data for flat ‘T’ shaped components, subjected to axial and shear loading.

The contributions of above in this area are very useful for many investigations. In the literature, it is not available for the cases like determining the stress concentration factors for critical and heavy components such as turbine rotors. Most of the researchers have concentrated or limited their works to only one type of analysis such as either for static or thermal or dynamic load.

In recent years, there has been an increased interest in the design and analysis of steam and gas turbines. In the power plant applications, a steam turbine rotor is indispensable equipment for power generation. The life of rotors in steam turbines has a severe impact on the power generation system. In the present work, a typical HP turbine rotor considered for the determination of stress concentration factors is described. A theoretical investigation of the turbine rotor using finite element method has been presented. Thermal and dynamic stresses are obtained using finite element analysis. Stress concentration factors for thermal and dynamic loads are calculated for HP rotor.

2. Description

A line diagram of HPT rotor is presented in Fig.1. The geometric and elastic properties are as follows

Rated output	=	210MW
Rated speed	=	3000RPM
Inlet steam pressure	=	150Kg/cm^2 (absolute)
Inlet steam temperature	=	535° C
Reheat steam temperature	=	535° C
Weight of the unit	=	475 tons
Overall length	=	16.975 m
Overall width	=	10.5 m
Rated frequency	=	50 c/s
Maximum permissible speed	=	3090 RPM
Minimum permissible speed	=	2850 RPM
Maximum frequency	=	51.5 c/s
Minimum frequency	=	47.5 c/s

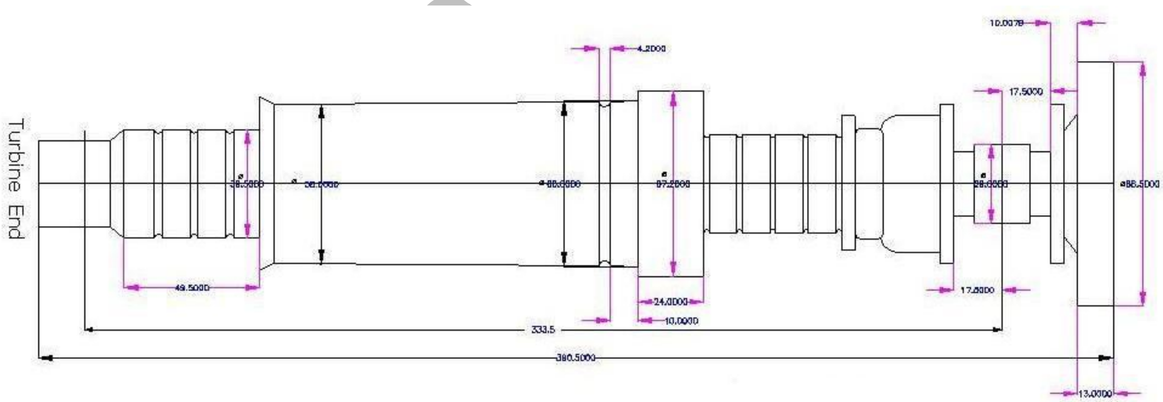

Fig.1. Line drawing of HPT rotor

3. Modeling

The chosen problem is considered as 2-D axi-symmetric problem to reduce the considerable time of computations and tedious computer efforts. The model consists more than 10,000 elements. Fig.2. shows the element 182 considered for meshing. FE modeling of the HP turbine rotor is shown in the Fig.3. Appropriate boundary conditions are incorporated in the analysis. The element can be used as either a plane element (plane stress, plane strain or generalized plane strain) or an axisymmetric element. It is defined by four nodes having two degrees of freedom at each node: translations in the nodal x and y directions. The element has plasticity, hyper elasticity, stress stiffening, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyper elastic materials.

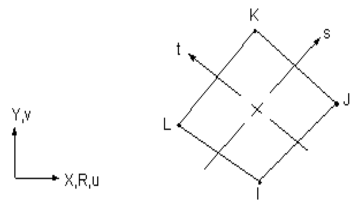

Fig.2. Plane 182 Element.

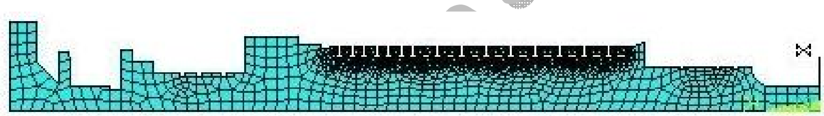

Fig.3.FE Model of HP Turbine rotor

Stress concentration factors for thermal and dynamic loads are computed in terms of stresses developed due to static loading on the rotors, load that is developed due to temperature rise and the load acting on the turbine blades due to steam pressure.

4. Analysis

4.1. Thermal Analysis

Variation of thermal stresses with respect to grooves is shown in Table.1. The results are plotted in Fig.4. Theoretical stress concentration factor based on thermal stress is given in Table.2. and plotted in Fig.5. The way the theoretical stress concentration factor is varying with respect of thermal stresses is shown in the Table.3 and plotted in Fig.6. The thermal stresses are obtained at the elevated temperatures of 530^0C, 535^0C, 540^0C, 545^0C and 550^0C.

It is observed that thermal stresses are increasing from 21037452 N/m^2 to 38472120 N/m^2 from the 1st groove to 16th groove and gradually decreasing to 31456543N/m2 at the temperature of 530^0C.

At 535^0C, thermal stresses are 22724947 N/m^2 at the 1st groove and gradually increasing to 41562415 N/m^2 up to 16th groove and gradually decreasing to a value of 33978375 N/m^2 at 25th groove.

At 540^0C, thermal stresses are 245249437 N/m^2 at the 1st groove and gradually increasing to 44910012 N/m^2 up to 16th groove and gradually decreasing to a value of 36765664 N/m^2 to the last groove.

It is observed that thermal stresses are increasing 26437439 N/m^2 to 48418607 N/m^2 from the 1st groove to 17th groove and gradually decreasing to a value of 39685680 N/m^2 to the last groove at the temperature of 545^{0}C.

It is observed that the thermal stresses are increasing 28574934 N/m^2 to 52300807 N/m^2 from the 1st groove to 16th groove and gradually decreasing to25th groove to the value of 42871153 N/m^2 at the temperature of 550^{0}C.

4.2. Dynamic Analysis

Variation of Dynamic stresses with respect to grooves is shown in Table.4. These readings are plotted in Fig.7. Effect of dynamic stresses on fatigue stress concentration factor is given in Table.5 and plotted in Fig.8. The way the fatigue stress concentration factor is varying with respect to dynamic stresses is shown in the Table.6. These readings are plotted in Fig.9. The dynamic stresses are obtained by considering self weight of rotor, blade weight and steam load as uniformly distributed load over a span of 1.712m at the operating and also elevated temperatures of 530^{0}C, 535^{0}C, 540^{0}C, 545^{0}C and 550^{0}C.

It is observed that dynamic stresses are increasing from 12937470 N/m^2 to 23683014 N/m^2 from the 1st groove to 17th groove and gradually decreasing to a value of 19378292 N/m^2 to a last groove of 25th at the operating temperature.

It is observed that the dynamic stresses are increasing from 21037452 N/m^2 to 38472120 N/m^2 from the 1st groove to 16th groove and gradually decreasing to25th groove to a value of 31456543 N/m^2 at the temperature of 530^{0}C.

At the temperature 535^{0}C, dynamic stresses are 22724947 N/m^2 at the 1st groove and gradually increasing to 41576847 N/m^2 up to 17th groove and gradually decreasing to the value of 33978375 N/m^2 to the last groove of 25th groove.

It is observed that dynamic stresses are increasing 24524943 N/m^2 to 44910012 N/m^2 from the 1st groove to 17th groove and gradually decreasing to 36765664 N/m^2 at the temperature of 540^{0}C.

At the temperature of 545^{0}C, dynamic stresses are 26437439 N/m^2 at the 1st groove and gradually increasing to 48418607 N/m^2 up to 17th groove and gradually decreasing to a value of 39685680 N/m^2 to 25th groove.

It is observed that the dynamic stresses are increasing from 28574934N/m2 to 52300807 N/m^2 from the 1st groove to 16th groove and gradually decreasing to25th groove to a value of 42871153 N/m^2 at the temperature of 550^{0}C.

5. Results

Table.1.Groove Number Vs Thermal Stresses

Groove No.	Thermal Stresses(N/m^2)				
	530^{0}C	535^{0}C	540^{0}C	545^{0}C	550^{0}C
1	2229249	2408066	2598804	2801463	3027964
2	2422833	2616144	2822343	3054316	3299177
3	2632442	2839178	3059697	3307780	3569646
4	2804383	3023476	3271780	3534691	3812208

5	2994934	3225314	3486410	3762866	4070039
6	3143808	3400445	3657083	3961840	4282636
7	3296652	3563048	3846093	4162439	4495434
8	3437682	3712696	4004899	4331479	4675247
9	3566470	3866618	4166767	4502227	4855343
10	3682588	3971418	4296352	4639338	5000376
11	3785610	4098014	4428796	4777954	5163865
12	3893735	4210450	4545795	4899771	5291008
13	3950646	4270460	4609087	4985339	5380403
14	4030731	4352432	4693057	5071529	5487849
15	4077125	4418466	4759806	5139074	5556268
16	4108211	4430052	4789757	5168394	5584894
17	4123563	4462486	4820238	5196819	5611058
18	4141408	4477198	4831643	5223397	5633807
19	4105353	4436727	4786510	5173113	5596535
20	4089028	4414703	4758471	5138425	5554565
21	4036775	4373173	4709571	5099085	5506303
22	3966582	4277010	4621930	4984097	5398001
23	3878015	4195611	4529923	4897665	5282124
24	3786762	4092926	4415204	4769709	5156442
25	3659498	3952875	4277134	4616834	4987416

Table.2 Thermal Stresses Vs Theoretical Stress Concentration Factor

Groove N0.	Thermal Stresses(N/m^2)					Theoretical Stress Concentration Factor(K_t)				
	530^{0}C	535^{0}C	540^{0}C	545^{0}C	550^{0}C	530^{0}C	535^{0}C	540^{0}C	545^{0}C	550^{0}C
1	2229249	2408066	2598804	2801463	3027964	1.7	1.84	1.98	2.14	2.31
2	2422833	2616144	2822343	3054316	3299177	1.71	1.85	1.99	2.15	2.33
3	2632442	2839178	3059697	3307780	3569646	1.74	1.87	2.02	2.18	2.35
4	2804383	3023476	3271780	3534691	3812208	1.75	1.88	2.04	2.2	2.37
5	2994934	3225314	3486410	3762866	4070039	1.77	1.91	2.06	2.23	2.41
6	3143808	3400445	3657083	3961840	4282636	1.78	1.93	2.07	2.25	2.43
7	3296652	3563048	3846093	4162439	4495434	1.8	1.95	2.1	2.27	2.45
8	3437682	3712696	4004899	4331479	4675247	1.82	1.96	2.12	2.29	2.47
9	3566470	3866618	4166767	4502227	4855343	1.84	1.99	2.15	2.32	2.5
10	3682588	3971418	4296352	4639338	5000376	1.85	2	2.16	2.34	2.52
11	3785610	4098014	4428796	4777954	5163865	1.87	2.03	2.19	2.36	2.55
12	3893735	4210450	4545795	4899771	5291008	1.9	2.05	2.22	2.39	2.58
13	3950646	4270460	4609087	4985339	5380403	1.91	2.06	2.23	2.41	2.6

14	4030731	4352432	4693057	5071529	5487849	1.94	2.09	2.25	2.44	2.64
15	4077125	4418466	4759806	5139074	5556268	1.95	2.12	2.28	2.46	2.66
16	4108211	4430052	4789757	5168394	5584894	1.97	2.13	2.3	2.48	2.68
17	4123563	4462486	4820238	5196819	5611058	1.99	2.15	2.33	2.51	2.71
18	4141408	4477198	4831643	5223397	5633807	2.02	2.18	2.35	2.55	2.75
19	4105353	4436727	4786510	5173113	5596535	2.03	2.19	2.36	2.55	2.76
20	4089028	4414703	4758471	5138425	5554565	2.05	2.22	2.39	2.58	2.79
21	4036775	4373173	4709571	5099085	5506303	2.07	2.25	2.42	2.62	2.83
22	3966582	4277010	4621930	4984097	5398001	2.09	2.25	2.44	2.63	2.85
23	3878015	4195611	4529923	4897665	5282124	2.11	2.28	2.46	2.66	2.87
24	3786762	4092926	4415204	4769709	5156442	2.14	2.31	2.49	2.69	2.91
25	3659498	3952875	4277134	4616834	4987416	2.15	2.33	2.52	2.72	2.94

Table.3. Grove Number Vs Theoretical Stress Concentration Factor

Groove No.	Theoretical Stress Concentration Factor(K_t)				
	530^0C	535^0C	540^0C	545^0C	550^0C
1	1.7	1.84	1.98	2.14	2.31
2	1.71	1.85	1.99	2.15	2.33
3	1.74	1.87	2.02	2.18	2.35
4	1.75	1.88	2.04	2.2	2.37
5	1.77	1.91	2.06	2.23	2.41
6	1.78	1.93	2.07	2.25	2.43
7	1.8	1.95	2.1	2.27	2.45
8	1.82	1.96	2.12	2.29	2.47
9	1.84	1.99	2.15	2.32	2.5
10	1.85	2	2.16	2.34	2.52
11	1.87	2.03	2.19	2.36	2.55
12	1.9	2.05	2.22	2.39	2.58
13	1.91	2.06	2.23	2.41	2.6
14	1.94	2.09	2.25	2.44	2.64
15	1.95	2.12	2.28	2.46	2.66
16	1.97	2.13	2.3	2.48	2.68
17	1.99	2.15	2.33	2.51	2.71
18	2.02	2.18	2.35	2.55	2.75

19	2.03	2.19	2.36	2.55	2.76
20	2.05	2.22	2.39	2.58	2.79
21	2.07	2.25	2.42	2.62	2.83
22	2.09	2.25	2.44	2.63	2.85
23	2.11	2.28	2.46	2.66	2.87
24	2.14	2.31	2.49	2.69	2.91
25	2.15	2.33	2.52	2.72	2.94

Table.4. Groove Number Vs Dynamic Stresses

Groove No.	Dynamic Stresses(N/m^2)					
	Operating	530^0C	535^0C	540^0C	545^0C	550^0C
1	12937470	21037452	22724947	24524943	26437439	28574934
2	14178348	22978702	24812108	26767743	28967831	31290147
3	15348290	25055756	27023485	29122397	31483672	33976130
4	16444978	26757931	28848394	31217586	33726142	36374062
5	17612870	28620914	30822522	33317679	35959609	38895088
6	18409324	30068563	32523139	34977715	37892525	40960745
7	19431621	31536566	34084975	36792660	39818896	43004407
8	20217210	32873512	35503393	38297641	41420625	44707976
9	20917185	34074770	36942449	39810127	43015180	46388920
10	21529227	35135699	37891440	40991648	44264091	47708767
11	22226027	36051667	39026804	42176949	45502103	49177273
12	22657251	36995044	40004209	43190385	46553571	50270776
13	22992820	37430173	40460234	43668535	47233313	50976330
14	23409107	38062136	41099959	44316477	47890387	51821687
15	23546089	38351585	41562415	44773246	48340835	52265183
16	23579686	38472120	41486064	44854591	48400408	52300807
17	23683014	38419112	41576847	44910012	48418607	52278061
18	23500257	38360715	41471042	44754167	48382883	52184395
19	23206392	37773908	40822923	44041328	47598512	51494476
20	22964311	37337657	40311452	43450458	46919887	50719737
21	22436321	36539153	39584082	42629011	46154719	49840686
22	21789498	35543153	38324791	41415500	44660744	48369595
23	21169559	34345020	37157756	40118536	43375391	46780286
24	20270842	33080888	35755513	38570908	41667842	45046316
25	19378292	31456543	33978375	36765664	39685680	42871153

Table.5. Dynamic Stress Vs Fatigue Stress Concentration Factor

Groove No.	Dynamic Stresses(N/m^2)						Fatigue Stress Concentration factor(K_f)					
	Operating	530^{0}C	535^{0}C	540^{0}C	545^{0}C	550^{0}C	Operating	530^{0}C	535^{0}C	540^{0}C	545^{0}C	550^{0}C
1	12937470	21037452	22724947	24524943	26437439	28574934	1.14	1.78	1.92	2.06	2.22	2.39
2	14178348	22978702	24812108	26767743	28967831	31290147	1.14	1.79	1.93	2.07	2.23	2.4
3	15348290	25055756	27023485	29122397	31483672	33976130	1.15	1.82	1.95	2.1	2.26	2.43
4	16444978	26757931	28848394	31217586	33726142	36374062	1.16	1.83	1.96	2.12	2.28	2.45
5	17612870	28620914	30822522	33317679	35959609	38895088	1.18	1.86	1.99	2.14	2.31	2.49
6	18409324	30068563	32523139	34977715	37892525	40960745	1.18	1.86	2.01	2.15	2.32	2.5
7	19431621	31536566	34084975	36792660	39818896	43004407	1.2	1.88	2.03	2.18	2.35	2.53
8	20217210	32873512	35503393	38297641	41420625	44707976	1.21	1.9	2.04	2.2	2.37	2.55
9	20917185	34074770	36942449	39810127	43015180	46388920	1.22	1.92	2.07	2.22	2.4	2.58
10	21529227	35135699	37891440	40991648	44264091	47708767	1.23	1.94	2.08	2.24	2.41	2.59
11	22226027	36051667	39026804	42176949	45502103	49177273	1.24	1.95	2.11	2.27	2.44	2.63
12	22657251	36995044	40004209	43190385	46553571	50270776	1.25	1.98	2.13	2.3	2.47	2.66
13	22992820	37430173	40460234	43668535	47233313	50976330	1.26	1.99	2.14	2.31	2.49	2.67
14	23409107	38062136	41099959	44316477	47890387	51821687	1.28	2.02	2.17	2.33	2.51	2.71
15	23546089	38351585	41562415	44773246	48340835	52265183	1.29	2.04	2.2	2.36	2.54	2.74
16	23579686	38472120	41486064	44854591	48400408	52300807	1.3	2.05	2.21	2.38	2.56	2.76
17	23683014	38419112	41576847	44910012	48418607	52278061	1.32	2.07	2.23	2.4	2.58	2.78
18	23500257	38360715	41471042	44754167	48382883	52184395	1.32	2.1	2.26	2.43	2.62	2.82
19	23206392	37773908	40822923	44041328	47598512	51494476	1.33	2.11	2.27	2.44	2.63	2.84
20	22964311	37337657	40311452	43450458	46919887	50719737	1.35	2.13	2.3	2.47	2.66	2.86
21	22436321	36539153	39584082	42629011	46154719	49840686	1.36	2.15	2.32	2.49	2.69	2.9
22	21789498	35543153	38324791	41415500	44660744	48369595	1.37	2.17	2.33	2.51	2.7	2.92
23	21169559	34345020	37157756	40118536	43375391	46780286	1.39	2.19	2.36	2.54	2.74	2.94
24	20270842	33080888	35755513	38570908	41667842	45046316	1.4	2.22	2.39	2.57	2.76	2.98
25	19378292	31456543	33978375	36765664	39685680	42871153	1.41	2.23	2.4	2.59	2.79	3.01

Table.6. Groove Number Vs Fatigue Stress Concentration Factor

Groove No.	Fatigue Stress Concentration Factor(K_f)					
	Operating	530^0C	530^0C	535^0C	540^0C	545^0C
1	1.14	1.78	1.92	2.06	2.22	2.39
2	1.14	1.79	1.93	2.07	2.23	2.4
3	1.15	1.82	1.95	2.1	2.26	2.43
4	1.16	1.83	1.96	2.12	2.28	2.45
5	1.18	1.86	1.99	2.14	2.31	2.49
6	1.18	1.86	2.01	2.15	2.32	2.5
7	1.2	1.88	2.03	2.18	2.35	2.53
8	1.21	1.9	2.04	2.2	2.37	2.55
9	1.22	1.92	2.07	2.22	2.4	2.58
10	1.23	1.94	2.08	2.24	2.41	2.59
11	1.24	1.95	2.11	2.27	2.44	2.63
12	1.25	1.98	2.13	2.3	2.47	2.66
13	1.26	1.99	2.14	2.31	2.49	2.67
14	1.28	2.02	2.17	2.33	2.51	2.71
15	1.29	2.04	2.2	2.36	2.54	2.74
16	1.3	2.05	2.21	2.38	2.56	2.76
17	1.32	2.07	2.23	2.4	2.58	2.78
18	1.32	2.1	2.26	2.43	2.62	2.82
19	1.33	2.11	2.27	2.44	2.63	2.84
20	1.35	2.13	2.3	2.47	2.66	2.86
21	1.36	2.15	2.32	2.49	2.69	2.9
22	1.37	2.17	2.33	2.51	2.7	2.92
23	1.39	2.19	2.36	2.54	2.74	2.94
24	1.4	2.22	2.39	2.57	2.76	2.98
25	1.41	2.23	2.4	2.59	2.79	3.01

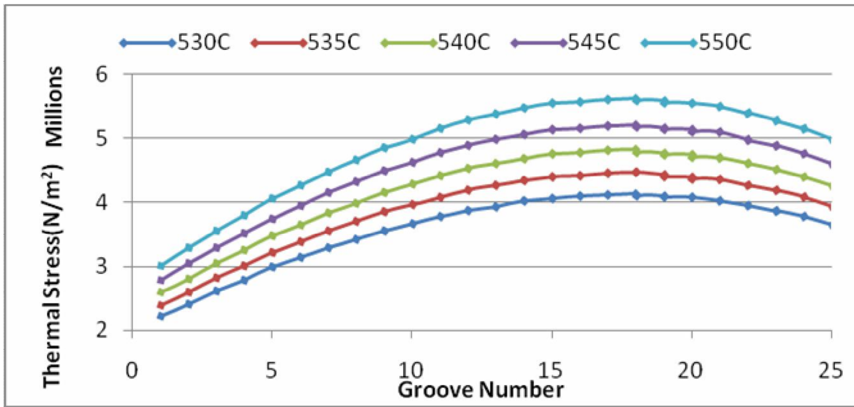

Fig.4. Variation of Thermal Stresses with respect to groove.

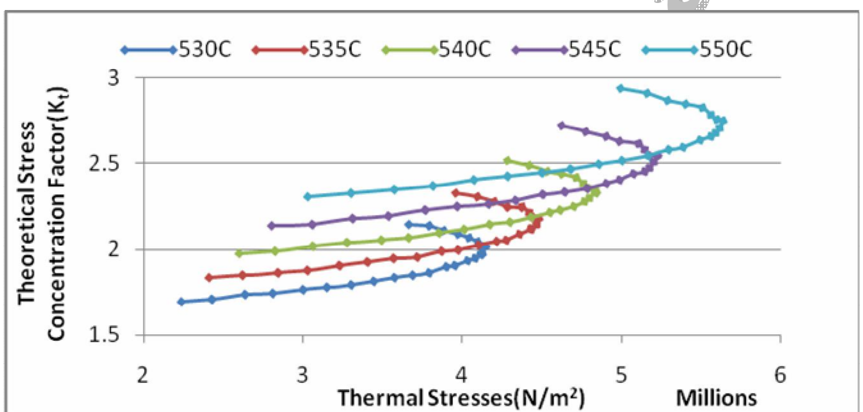

Fig.5. Theoretical Stress Concentration Factor with respect to Thermal Stresses.

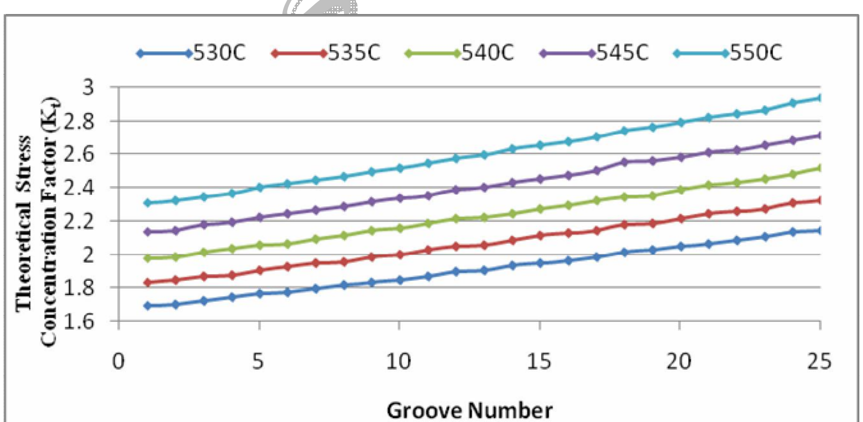

Fig.6. Variation of Theoretical Stress Concentration Factor with respect to groove.

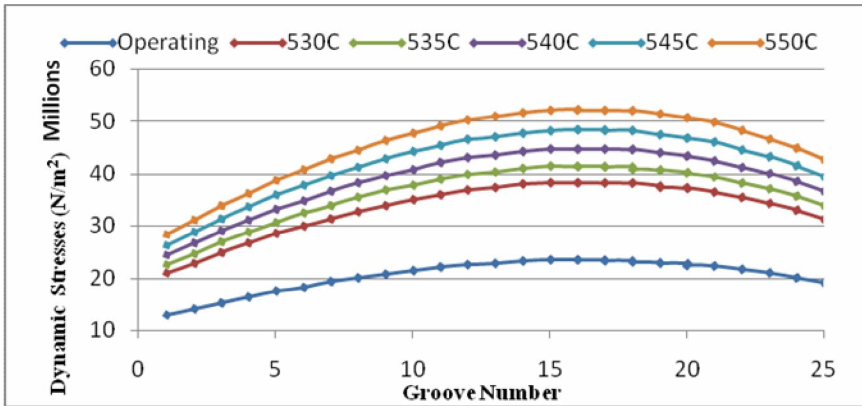

Fig.7. Variation of dynamic stress with respect to groove

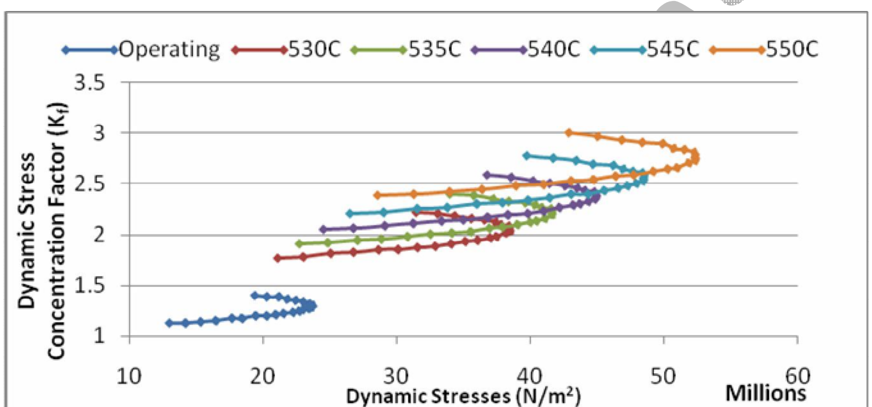

Fig.8. Dynamic Stress Concentration Factor with respect to Dynamic Stress.

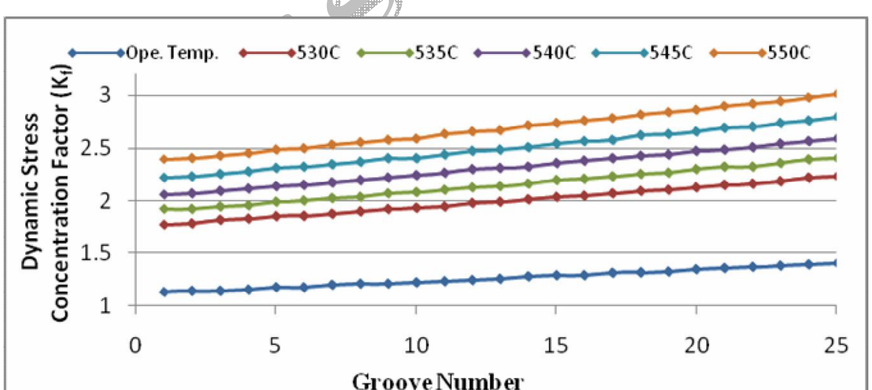

Fig.9. Variation of Dynamic Stress Concentration Factor with respect to groove

6. Conclusion

In this paper an attempt has been made to compute stress concentration factors due to thermal and fatigue loadings. The methodology adopted gives a systematic theoretical investigation to predict high concentration of stress and its impact on the life of the rotor. At the end of the analysis it is concluded that at 545^0C there will be a high concentration of stress and hence it is suggested to operate the turbine corresponding to inlet steam temperature which is less than 545^0C.

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