Important track design parameters to cater semihigh speed & heavier axle loadstrains

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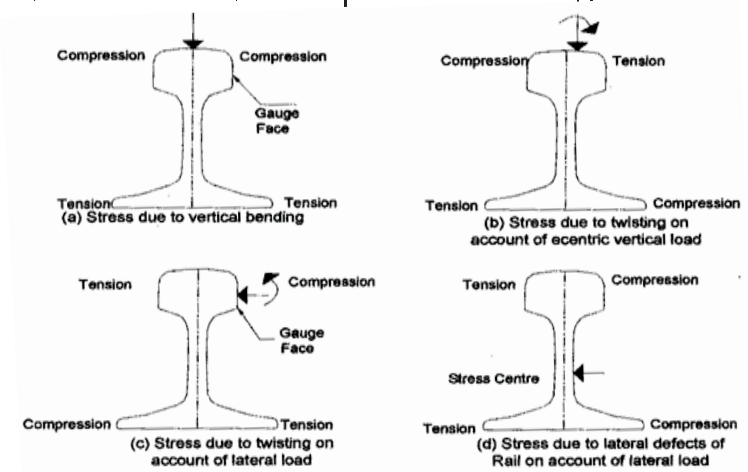
Synopsis

The paper deals with consideration of important track design parameters i.e. Static vertical load intensity, Dynamic Augment, Rate of Track geometry deterioration, Target defect wave length for track geometry correction, Implications of specific locations such as curved track, abrupt change in sub grade stiffness to cater semi high speed & heavier axle load trains, including proposed action to deal with.

1. Introduction: A case of Tokaido Shinkansen

1.1 The loading considered on Indian Railways for calculation of rail stresses (track stresses) are explained in the figure below:



Stresses at centre of foot = stress due to vertical bending, Stresses at edge of foot = a + b – c + d

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The magnitude of rail stresses considered on various accounts is as under :

SN	ITEM	VALUE IN KG/MM^2 FOR 90 UTS RAIL	%AGE OF PERMISSIBLE STRESS
1.	Ultimate tensile strength	90.0	
2.	Yield strength (52% of average value of observed (UTS) i.e. stress at 2% strain (proof strain)	46.80	
3.	Stress for unforeseen reasons such as flexed laying on curve,uneven heating of rail faces etc. @ 10% of yield strength	4.80	10.2%
4.	Thermal stresses in LWR	10.75	23%
5.	Residual stresses in rails	6.00	12.8%
6.	Induced stresses due to rolling stock (permissible stresses on yield consideration).	25.25	54%

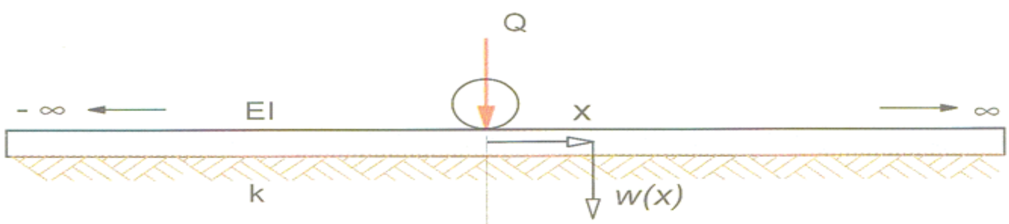
Note: The rail stresses for unforeseen reason includes flexed laying of rails on a 4° curve & one sided radiation of sun. However it does not account for impact of wheel irregularities, rail/weld irregularities being of instantaneous nature.The factor of safety of 1 is considered i.e. rail is being loaded to full yield strength.

2. The mixed traffic involving semi high speed passenger trains (with speed 160 to 200 kmph) and heavier axle load (with axle load 30 to 32.5t) freight trains pose variety of challenges to the track. The design of track components & evolving track maintenance features/ practices for such traffic conditions requires proper understanding of various important track design parameters, these are discussed hereunder.

2.1 Static stresses due to vertical bending

a) Static Stresses in Rail

Considering track as an infinitely long rail (CWR track) with bending stiffness EI, continuously supported on an elastic foundation with track modulus (μ),



The bending moment in rail follows following equation

$$M(X) = \frac{QL}{4}\mu(\chi), \text{ Where :- } \mu(\chi) = e^{-x/L}\left[\cos\frac{x}{L} - \frac{\sin x}{L}\right] x \geq 0$$

Maximum BM under single load $= \frac{QL}{4}$,

where L = characteristic length = $\left(\frac{4EI}{U}\right)^{1/4}$

Mean stress in rail $\sigma_{mean} = \frac{QL}{4z}$ where z is section modulus relative to rail foot.

b) Static Rail seat load for sleeper

Considering track as beam of infinite length supported on elastic foundation, the Static Rail seat load is governed by following equation : $Q_s = QS\left(\frac{U}{64EI}\right)^{1/4}$

Wherein Q is static wheel load i.e. axle load divided by 2, S is sleeper spacing

U is track modulus i.e. load per meter length of track to cause unit deflection in track

EI – bending stiffness of rail.

a) Vertical stress on ballast bed

$$\sigma_{sbmean} = \frac{Fmean}{Asb} = \frac{Q}{2L\,Asb} = \frac{Q\,S}{2\left(\frac{4EI}{U}\right)^{1/4}} = \frac{QS\left(\frac{U}{64EI}\right)^{1/4}}{Asb}$$

Where Asb=contact area between sleeper & ballast bed for half sleeper.

Implications: The Heavier axle load means higher wheel load, which will result into higher B.M. & higher stress in rail, higher static rail seat load on sleeper & higher vertical stress on ballast bed & formation.

High speed passenger trains		Heavier axle load freight trains (increase w.r.t 22.5 t axle load)	
160 kmph	200 kmph	30 t	32.5 t
No change		**33 % increase**	**44% increase**

Action proposed-1 :

The fatigue life of track components mainly Rail, sleeper, Rubber pad, ERC required to be evaluated/ assessed for higher stress cycle. Otherwise under higher stress cycle loading, fatigue failures associated with sudden & abnormal rate of failures of track components may take place, posing serious problems of safety of traffic.

2.2 Stresses due to Lateral load

The generation of lateral / flange force will depend upon speed, axle load & conicity of wheel & play. Under semi high speed & heavier axle load the lateral flange force will increase. The play needs to controlled & conicity of wheel can be 1 in 40 in place of 1 in 20, accordingly rail profile will require to be re - designed.

3. Dynamic Augment

As per Indian Railway Works practice (RDSO guidelines) the Dynamic Augment is governed by C-100 Report. The dynamic augment reported for various rolling stock at their maximum permitted speed, based on RDSO trials in June-2005 is as under:

ROLLING STOCK	SPEED (KMPH)	DYNAMIC AUGMENT USING WILD (%AGE)
Box N	75	55% approx.
Box NHS	75	50% approx.
WDM2	110	95% approx.
BCN	75	50% approx.

Now as per European practice, the Dynamic Augment is based on the following equation:

$\sigma_{max} = DAF \times \sigma_{mean}$

where σ_{max} is maximum stress in rail /sleeper /ballast bed

σ_{mean} is mean stress in rail /sleeper / ballast bed

DAF is dynamic amplification factor = $1 + t\,\phi\,(1 + \frac{V-60}{140})$

t is multiplication factor of S.D, which depends upon confidence interval, is a factor which depends upon track quality. The value of t & ϕ is given here under:

t	*Probability*	*Application*
1	68.3%	Sub grade Contact stress
2	95.4%	Ballast bed
3	99.7%	Rail stresses, sleepers, fastening

Track Condition	ϕ
Very good	0.1
Good	0.2
Bad	0.3

Note: The maximum stress is generated in rail foot centre due to repeated loading causing fatigue fractures.

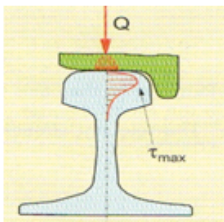
Implications: The high speed means higher dynamic augment, which will result into higher BM & higher stress in rail, higher rail seat load on sleeper & higher vertical stress on ballast bed & formation

High speed passenger trains (Increase w.r.t 130 kmph)		Heavier axle load freight trains	
160 kmph	200 kmph	30 t	32.5 t
14%	**33%**	**No change**	

Action proposed-2:

The maximum stress for track components mainly Rail, sleeper, Rubber pad, ERC under IR track maintenance conditions required to be evaluated/ assessed for higher stress cycle. The concrete sleeper & rubber pad will require to be redesigned. Rails with better metallurgical properties at par with international practices, along with efficient handling practices needs to be introduced.

4. Rail Wheel Contact Stress



The Rail wheel contact stress is governed by Equation: $t_{max} = 4.13\sqrt{\frac{Q}{r}}$

Where Q is static wheel load and r is radius of wheel negotiating the track.

Implications:

High speed passenger trains		Heavier axle load freight trains (increase w.r.t 22.5 t axle load)	
160 kmph	200 kmph	30 t	32.5 t
No change		**15 % increase**	**20% increase**

Action proposed-3:

Rail grinding & efficient rail top profile will help the situation.

5. Forces due to wheel flat & bad weld

i) The wheel flat causes generation of higher dynamic load getting transferred to track. The additional bending moment in rail due to wheel flat is given by the equation – $MF = 1.57 \times (10^5 + 11Q)\sqrt{f}$
Where MF is additional bending moment by rail in KG-cm, Q is wheel load in KG, f is depth of Flat - in mm

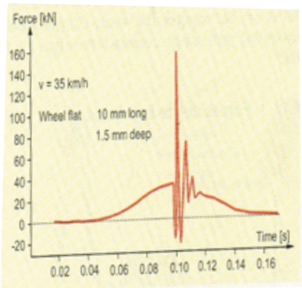


Figure: vertical force under passage of wheel flat

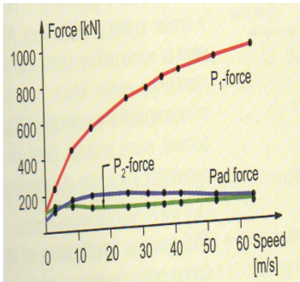


Figure: P1 & P2 forces under passage of wheel flat

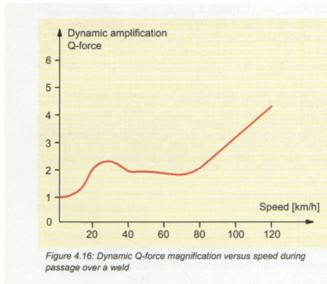


Figure: Dynamic amplification due to bad weld

Note: Forces at frequencies above 500 HZ referred to P1 forces are important as far as wheel / rail contact stresses are concerned. The forces at frequencies below 100 HZ referred as P2 forces are more or less independent of speed

Dynamic force amplification versus speed during passage over bad weld

ii) The dynamic amplification of vertical force during the passage over a poor weld is presented as a function of speed. The dynamic amplification ($\Delta Q / Q$) of vertical load is expected to be very high, may be as high as 400%.

Note: IR practice does not account impact of wheel flat, rail/weld irregularities in rail stress calculations being of instantaneous nature.

Implications: High frequency dynamic loads due to poor welds, corrugation and wheel flats are very detrimental to the track. Concrete sleepers are very susceptible to these loads. The properties of rubber pad carries maximum significance. The limiting depth of wheel flat needs to be specified instead of length of wheel flat.

Action proposed-4:

The limiting depth of wheel flat needs to be specified instead of length of wheel flat. Quality of AT welding requires continuous monitoring & updating to keep par with international practices

6. Target defect wave length measurement& correction

The target wave length defects are those critical defects, which are required to be measured during track recording & subsequently eliminated during track maintenance operation. The wavelength of critical defects depends upon speed of the train and natural frequency of suspension system of the train. The critical defect wave length for high speed passenger train and heavy axle load freight train is worked out based on following principles:

- The maximum disturbance shall occur when wave length of defect λc is such that at a particular speed of train the forced frequency of oscillation (generated due to defect) matches with natural frequency of suspension system.
- The wave length of defect which shall be critical (in vertical mode only) for various types of rolling stock, i.e. which are required be eliminated while track tamping is given below

Rolling stock	Natural frequency of Suspension (fn)	Speed V (in kmph)	Critical wave length (λc)=V/fn
Box N	3.5	75	5.95 m
Heavy axle load wagon	3.0 (assumed)	100	9.25 m
ICF coach	1.2	130	30 m
High speed coach	1.0 (assumed)	160	44.4 m
		200	55.5 m

- The small wave length defects (in the range of 5 to 10 m) shall affect running of goods train and longer wave length defect (in the range of 25 m to 55 m) shall affect running of passenger trains.

- To detect these defects (unevenness) the chord length for measurement should be in the wider range of 3.6 m to 27.5 m (As the chord length for measuring defect should be = $\lambda c/2$, To achieve transfer function TF=1). Similar exercise needs to be done for lateral mode also for fixing up critical alignment defects.

Note: The railway track built on relatively soft subgrade, the critical regime is reached when the train velocity is near the sheer wave velocity of subgrade. The magnitude of sheer wave velocity is determined by equation, where $Cs=\sqrt{\mu/\rho}$ μsheer modulus and p is density of material. For subgrade of soft clay, the sheer wave velocity lies between 150 to 250 kmph, accordingly, the track response is expected to be amplified when the speed is in the range of 160 to 200 kmph.

Action proposed-5:

The track monitoring with defect measurement using appropriate chord length is required, to pick up wider& relevant spectrum of track defects in horizontal & vertical mode.

7. Rate of crack propagation due to fatigue flaw in rail /weld

The science of fracture mechanics, deals with only propagation of cracks & fractures, In linear-elastic fracture mechanics, the crack tip stress intensity factor 'K', is used to characterize the magnitude of the complex stress and strain fields at the tip of a crack.

The magnitude of 'K' is simply a function of the nominal stress (σ) in the cracked structure, the size of the crack (a) and shape factor (Cs) which depends upon the geometry of the structure and the crack, such that $K=Cs\Delta\sigma\sqrt{a}$

Where K = the difference between the maximum & minimum nominal stress levels in the fatigue cycle. At fracture, the critical stress intensity K_{ic} is attained, with the corresponding critical stress c and the critical crack depth a_c

Important points on rate of crack propagation

The fracture toughness of rail steel decreases with increasing tensile strength. The values of a_c & RFR (rail fracture resistance) decrease as rail strength increases. The critical crack size obtained using the above stress values, works out 5-6mm for 90 UTS rails.

Flaw size smaller than $\lambda/2$ is considered as undetectable, The USFD testing can detect a flaw size= > 1 mm approx. A crack of 1mm size exists in the rail at the time of detection, then the failure can be apprehended after passage of 8 GMT in 90 UTS rails.

Implications: The rate of crack propagation i.e. fatigue failure will increase under heavy axle load & high speed trains.

Action proposed-6:

The frequency of USFD testing of Rail & weld will require to be increased, Use of spurt car will help to implement it.

8. Location specific additional factors:

8.1 CurvedTrack geometry

Presently curves are designed based on maximum & minimum speed of trains running in the section. In order to achieve even wear on both rails under heavier axle load freight trains & to control discomfort under high speed passenger train, the design cant should be worked on the basis of equilibrium speed using following equation: (Russian Formula)

$$Veq = \sqrt{\frac{\sum_{i=1}^{m} niwiv_i^2}{\sum_{i=1}^{m} niwi}}$$

Where : n_i= number of trains in i^{th} set, w_i = load of each train in i^{th} set
v_i = speed of each train in i_{th} set, m = number of sets of trains

8.2 Abrupt change in sub grade stiffness

The change in stiffness causes increased dynamic forces, the extent of which is determined by speed, stiffness ratio, damping and the length of transition. The semi high speeds trains will require larger transition track to introduce gradual change in stiffness of subgrade on the approach of girder bridges, level crossing, point and crossing. This will help in controlling rate of track geometry deterioration at locations where there is abrupt change in subgrade stiffness.

8.3 Abrupt change in vertical alignment

The changes in vertical alignment of track lead to increasingly pronounced vertical acceleration in the vehicle causing higher dynamic augment and passenger discomfort. The semi high speeds trains will generate higher dynamic forces& passenger discomfort at the locations of abrupt change in vertical alignment such as junction of steep gradients, Therefore to control the dynamic forces & rate of track geometry deterioration at these locations provision of vertical curves with appropriate radius becomes mandatory

Action proposed-7:

The transition tracks at locations involving abrupt change in subgrade stiffness needs to evolved & introduced immediately in new constructions & in phased manner during complete track renewals on existing tracks. In additionbetter maintenance practices with semi mechanized/ fully mechanized spot attention for these locations needs to be evolved.

8.4 Negotiating points & crossing assembly:

The permitted speed on points & crossing assembly is governed by turn out features mainly switch entry angle, lead curve radius having no transition & cant, straight crossing & gap at nose of crossing.

Action proposed-8:

Improving speed potential of turnout assembly will require introduction of thick web switch to have sturdy switch assembly, weld able Xing to avoid joints, swing nose Xing / curved Xing to continue curved track in Xing portion. All this will bring adequate improvement in existing 1 in 12 turnout assembly (i.e. without changing yard layout).

9. Rate of track geometry deterioration:

The mechanism of track geometry deterioration phenomenon is complex. The magnitude of settlement in the ballast depends upon magnitude of axle load, number of loading cycles, speed & percentage content of fouling material.The Rate of track geometry deterioration is governed by following equation based on ORE study report no: D141 & D17

$$E = K, T^{\alpha} P^{\beta} V^{\gamma}$$

Where E = deterioration since renewal or last maintenance operation, T -= tonnage, P = axle load (static + dynamic) V = speed,K, α, β, γ= constants.

phenomena	α	ß
Rail fatigue	3	3
Track geometry deterioration	1	3

Implications:

High speed passenger trains (Increase w.r.t 130 kmph)		Heavier axle load freight trains (increase w.r.t 22.5 t axle load)	
160 kmph	200 kmph	30 t	32.5 t
51%	**136%**	**137 % increase**	*200% increase*

9.1 Characteristics of track geometry deterioration

i. The track quality i.e. vertical quality and alignment deteriorate linearly with tonnage or time between maintenance operations after the first initial settlement; however, this trend is not always the case, for sections with high deterioration rates.

ii. The rate of track deterioration is very different from section to section even for apparently identical sections carrying the same traffic.

iii. The rate of track deterioration appears to be constant parameter for a section of track, regardless of the quality achieved by the maintenance machine;

iv. In general tamping machines improves the quality of a section of track to a more or less constant value.

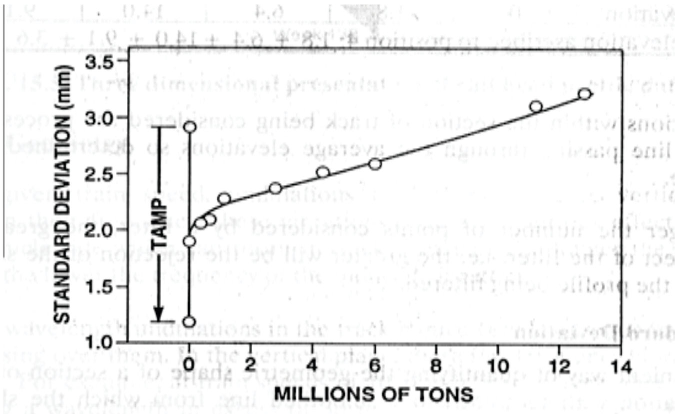


Fig: Track quality changes during maintenance Cycle

9.2 Concept of Inherent Track Shape

It has been observed that track appears to have an inherent shape, which remains with it throughout its life. This inherent shape appears to be introduced into the track at the time of its original construction, Achieving subsequent changes in the inherent track shape is very difficult. To a large extent, Inherent Track Quality is a function of Inherent Track shape.

9.3 Track inherent Quality

(Please refer fig next page) The downward pointing arrow indicates tamping operations.The track shown in the upper part of the sketch has a standard deviation of 1.5mm and has required 2 tamping operations in 5 years to maintain the track quality at that level. Such a track can be regarded as having a good inherent quality.

The track shown in the lower part of the sketch however, has a standard deviation of 3.2mm and has required 6 tamping operations in the same 5 years period, to maintain the track quality at that level Such a track can be regarded as having a relatively poor inherent quality.

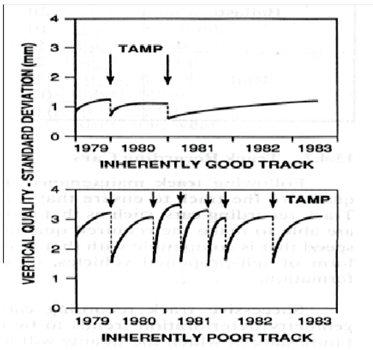


Figure: shows two sections of track, 1 km apart, both carrying the same traffic.

Note: The inherent track shape/quality affects the dynamic behavior of track under train loads. It is reported that wheel rail forces for = 1 mm (0-25m wave band) DAF95< 1.67, = 1.5 mm DAF95 < 2 according to Euro code.

9.4 Factors affecting track geometry deterioration

The studies undertaken by ORE D-117 & D161, to analyze the effect of different types oftraffic, track construction and maintenance machine on the quality of the track & its rate of deterioration, shows that:-

The factors governing the rate of deterioration are not obvious and that the unknown factors in the track are the most important in determining both the average quality and the rate of deterioration. While the results of these tests on the effects of these variations were not very conclusive, the committee (ORE D-117) nonetheless felt that:

- The quality of the track on relaying was the most important factor.
- It is very difficult to differentiate statistically for the effects of traffic, track construction and foundation on the rate of deterioration, even for sections of nominally similar track, however In general, a high rate of track deterioration in individual areas of a larger section can be linked to characteristics, which are:
  - ➢ Local geometry faults present from the start (Inherent track shape & track inherent quality)
  - ➢ Singular features (rail bridges, level crossings, etc.) i.e. locations involving abrupt change in the subgrade stiffness
  - ➢ Sub-layers of inferior quality formation
  - ➢ Welds of inferior quality (Short wave length defects)

Actions proposed-9:

i) The quality of track on relaying is the most important factor to affect the rate of track geometry deteriorations. Track can be constructed such that it has a good inherent quality & the inherent quality of existing track can be improved using Design over lift tamping & High lift design tamping.

ii) The surface defects in the rail wheel contact area, i.e. cupped welds, low joints, poor geometry on welds, poor support conditions at the joints, corrugation on rail top, wheel flat, Inadequate availability of clean ballast cushion, poor condition of sub grade, generates higher dynamic forces. These needs to be monitored regularly

iii) Efficient semi mechanized / fully mechanized methods to be introduced for isolated spot attention /slack packing.

iv) Proper maintenance of track machines with adequate & proper pre tamping, post tamping attention, for getting satisfactory quality of tamping output is a pre requisite to lengthen tamping cycle.

v) Overloading of freight stock, Poor maintenance of rolling stock is causing higher lateral forces. Better bogie designs to have improved rail wheel interaction are required. The bogie with low un-sprung mass, efficient damping characteristics improves rail wheel interaction.

10. Recommendations:

1. The fatigue life of track components is required to be evaluated/ assessed for higher stress cycle, including maximum stress under mixed traffic of semi high speed & heavier axle load conditions, to avoid & settle issues related to sudden fatigue failures of track components.

2. The quality of track on initial laying / relaying is the most important factor to affect the rate of track geometry deteriorations, therefore track laying quality is to be given due importance.

The concept of Design over lift tamping & high lift design tamping needs to be introduced on I.R

3. The Experience of foreign railways having similar traffic situations including rolling stock design needs to be studied & utilized to plan& cater for heavier axle load & semi high speed routes of Indian Railways.

References:

i) Book Modern Railway Track –Coenraaad Esveld

ii) Item no 1078- review of Rail stress calculation methodology-76th TSC meeting jan-2006