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Laying and Maintenance of CWR Track

Pose et maintenance de la voie en longs rails soudés
Verlegung und Instandhaltung von lückenlosem Gleis

UNION INTERNATIONALE DES CHEMINS DE FER
INTERNATIONALER EISENBAHNVERBAND
INTERNATIONAL UNION OF RAILWAYS

Leaflet to be classified in Volume :

VII - Way and Works

Application :

With effect from 1 January 2005
All members of the International Union of Railways
Improved knowledge of forces in CWR track (including switches)

Record of updates

1st edition, January 1986	First issue
2nd edition, March 2005	Overhaul of Leaflet Adaptation to the editor’s guide M1 - New lay-out

The person responsible for this leaflet is named in the UIC Code

Contents

Summary

This leaflet contains guidelines for the use, installation and inspection of ballasted track with continuous welded rails (CWR), and also lists the associated safety criteria. It is based on the practical experience of several railways and a large number of tests and theoretical studies carried out over a period of more than 40 years. It also includes the results of studies undertaken by *ERRI Committee D 202*.

The leaflet has been enhanced by inclusion of a point on safety aspects and a point on case studies conducted using the CWERRI and CWR-BUCKLE models. A new safety criterion has been formulated on the basis of maximum and minimum buckling temperatures ($T_{b,max}$ and $T_{b,min}$). The parameters were selected to reflect a maximum temperature which corresponds to 50% of the buckling energy level. In addition, a concept of buckling safety based on risk assessment methodology has been introduced.

The case studies include examples of high-speed, main-line passenger tracks on both concrete and wooden sleepers, together with secondary and freight tracks.

Permissible rail temperatures for the various scenarios studied are presented graphically.

1 - Introduction

1.1 - Purpose

This leaflet contains guidelines for the installation and use of ballasted track incorporating continuous welded rails (CWR), together with details of inspection methods and safety criteria. It is based on the practical experience of several railways and a large number of tests and theoretical studies undertaken over more than 40 years. It also includes the results of international work on this topic carried out by *ERRI Committee D 202*. This leaflet replaces UIC Leaflet 720, 1st edition, dated 1986 on the same topic.

1.2 - Scope

1.2.1 - Use of CWR track

CWR is now in widespread use on most railways, since, although the construction costs of CWR are similar to those of jointed track, CWR has important technical, ecological and economic advantages, in particular, a significant reduction in maintenance costs.

CWR is also a prerequisite for high-speed services.

1.2.2 - Advantages of CWR track

The main advantages of CWR track are:

- reduced maintenance costs,
- fewer rail defects and failures,
- reduced wear on vehicles,
- reduced noise and vibration emissions,
- better ride comfort,
- lower energy costs for traction,
- easier mechanisation of track installation and maintenance.

All these features translate into reduced life cycle costs compared to jointed track.

1.2.3 - Consequences

The use of CWR requires precautions in the design of the track structure, and in its installation, maintenance and inspection. It also requires an understanding of the effects of temperature, rolling-stock and track features, on track stability and rail failures.

1.3 - Definition

1.3.1 - CWR track

CWR track is track in which the free expansion and contraction of the rails caused by temperature changes are constrained, by artificially introducing a controlled expansion into the rails prior to installation of the track fastenings.

Consequently high longitudinal forces are induced in the rails as a result of temperature changes.

Resistance to longitudinal movement of the rails, under the action of these forces, is secured through the clamping action of the rail fastenings and the restraining effect of the boxing ballast.

Total longitudinal force P in the track, either tensile or compressive, is given by:

$$P = 2\alpha EA\Delta T$$

where: α = coefficient of expansion of steel
E = Young's modulus of steel
A = rail cross-sectional area
ΔT = change in temperature from the "stress-free temperature"

The longitudinal stresses in each rail are given by:

$$\sigma = \alpha E\Delta T$$

The change in temperature from the "stress-free" condition can reach values as high as 40-45°C resulting in rail forces of 800 kN and rail stresses of up to 100 N/mm^2 in UIC 60 rails.

1.3.2 - Aim of the leaflet

The aim of the leaflet is to explain the parameters affecting track stability and to set out the methodology for ensuring the stability and safety of CWR track.

1.3.3 - Structure of the leaflet

The leaflet is structured around the following points:

2. Key parameters	Effect of track structure, layout, geometry and temperature on track stability.
3. Additional parameters	Effect of rolling stock, bridges, switches and crossings, substructure, etc.
4. Installation of CWR track	Requirements for installation.
5. Maintenance	Requirements for maintenance, inspection and repair.
6. Elimination of problems	Track buckling and distortion.
Appendix A. Safety	Methodology for risk assessment and establishment of safety criteria.
Appendix B. Case studies	Case studies using mathematical model CWERRI: examples and application of results.

2 - Key parameters

2.1 - Rails

All flat-bottom rail profiles are suitable for CWR track.

It is recommended that intermediate section rails are introduced where it is required to join rails having cross sectional areas which differ by more than 22%.

New rails should not be drilled.

It is recommended that serviceable rails undergo ultrasonic examination prior to CWR conversion.

Existing fishbolt holes should preferably be removed prior to CWR conversion but this is not essential, particularly in lower-speed and lower-tonnage track categories.

2.2 - Fastenings

Only fastening systems which provide adequate guaranteed longitudinal and torsional resistance to rail movement relative to the sleepers, shall be used in CWR.

The end of a CWR section of track over which rail movement can occur is called "the breathing length".

Expansion switches can be fitted at the end of a section of CWR track where it abuts an adjoining section of jointed track or at a specific location such as a bridge, etc.

2.3 - Type and spacing of sleepers

Concrete, wooden or steel sleepers are suitable for use in CWR. However, the type and shape of the sleeper can have a significant effect on the lateral resistance and stability of the track.

The mass of the sleeper, the surface area of the sleeper end and the sleeper spacing, have a major effect on the lateral resistance. Steel sleepers require a particular tamping technique to ensure that the ballast penetrates the hollow underside of the sleeper completely.

2.4 - Ballast-bed dimensions

Satisfactory longitudinal and lateral resistance of the track depends on the mass, particle size, shape, cleanliness and compaction of the ballast.

The particle size shall be within the range 22,4/63 mm and the individual particles shall be sharp-edged and uniformly distributed.

The recommended minimum depth of ballast below the sleeper soffit is 300 mm, and not less than 200 mm.

The recommended minimum width of ballast shoulder, i.e. the horizontal distance between the end of the sleeper and the slope of the ballast, is 400 mm for speeds up to 160 km/h and 500 mm for higher speeds. The top of the ballast shoulder shall be at least level with the top of the sleeper.

The width of the ballast shoulder may, with advantage, also be increased to the higher value in sharp radius curves or where tilting trains operate.

The lateral resistance of the track can be increased to a limited extent by widening and raising the level of the ballast at the sleeper ends.

The lateral and longitudinal resistance of the track depends to a large extent on the degree of compaction of the ballast, being greatest when the ballast is fully compacted and least when the ballast is freshly tamped (see also point 3.3 - page 9).

The depth of the ballast and the width of the ballast shoulder may, during installation, fall below the above recommendations temporarily, provided high ambient temperatures can be guaranteed not to occur, or a temporary speed restriction is imposed. However, the full ballast dimensions should be obtained prior to commencement of operating at line speed.

2.5 - Alignment

The quality of the alignment has a significant effect on the lateral resistance of CWR track. A greater degree of misalignment is usually found in curves compared with straight track.

The minimum curve radius in which CWR track may be safely installed depends on the rail section, the fastenings, the type of sleeper, the ballast profile and the anticipated longitudinal thermal stresses. CWR may be installed on curves sharper than 300 m radius provided special measures, such as fitting anchoring devices to the sleepers, are taken.

2.6 - Track geometry

Major errors in alignment can lead to track buckling at high rail temperatures. It is essential therefore that alignment errors should be minimised by correct maintenance procedures. The magnitude of the maximum permissible alignment error in any section of CWR track depends on the rail section, sleeper type, fastening type, ballast condition, stability of the ballast bed and the prevailing temperature.

2.7 - Important rail temperatures

The following rail temperatures must be known prior to the installation of CWR track:

2.7.1 - Mean rail temperature

The mean rail temperature T_m is the arithmetic mean between the maximum rail temperature T_{max} and the minimum rail temperature T_{min}.

$$T_m = \frac{T_{max} + T_{min}}{2}$$

NB : These temperatures are not generally the same as the maximum and minimum air temperatures.

2.7.2 - Nominal rail temperature

The nominal rail temperature T_s is the optimum temperature at which the track should be fastened down. It should be several degrees above the mean rail temperature in order to limit the magnitude of compressive stresses.

$$T_s = T_m + X \text{ (where X ranges between 0 and 10°C)}$$

2.7.3 - Notional temperature

The notional rail temperature is the temperature of the rails prior to the commencement of work.

2.7.4 - Installation temperature range

The installation temperature range is the nominal temperature ± 3°C (for example).

2.7.5 - Installation temperature

The installation temperature T_f is the specified equivalent rail temperature at which the fastenings shall be tensioned. It is, by definition, within the range specified in point 2.7.4.

2.7.6 - Initial temperature

The initial temperature is the rail temperature immediately prior to the commencement of stressing the rails.

2.7.7 - Stress-free temperature

The stress-free temperature T_n is the temperature at which there are no thermal stresses in the rails.

2.7.8 - Maximum temperature

The maximum rail temperature T_{max} is the maximum expected in a particular location.

2.7.9 - Minimum temperature

The minimum rail temperature T_{min} is the minimum expected in a particular location

2.8 - Additional temperature characteristics

The following additional temperature characteristics may be known prior to commencement of work and may be laid down in rules or calculated from mathematical modelling:

2.8.1 - Maximum Critical Temperature

The maximum critical temperature $T_{b,max}$ is the predicted rail temperature from mathematical modelling at which track buckling is almost a certainty.

2.8.2 - Minimum Critical Temperature

The minimum critical temperature $T_{b,min}$ is the predicted rail temperature from mathematical modelling below which track buckling is unlikely to occur.

2.8.3 - Allowable Temperature

The allowable temperature T_{all} is the temperature which provides a margin of safety against a predicted likelihood of track buckling.

2.8.4 - Increment

Increment ΔT is an incremental margin from the allowable temperature, either up or down, which provides either a lesser or greater margin of safety against buckling.

3 - Additional parameters

3.1 - Subgrade

The characteristics of the subgrade shall be such as to ensure the long-term stability of the CWR track.

On soft ground (e.g. peat), the technical feasibility of using CWR track shall be established and, if possible, special precautions shall be taken. It is not recommended to install CWR in locations which are affected by subsidence (e.g. coal mining areas, etc.) since large uncontrolled stresses or deformations can occur in the track.

The following subgrade characteristics are of particular importance:

- good stability, little likelihood of subsidence, unaffected by frost;
- adequate bearing capacity for the type of track and traffic carried;
- good drainage.

3.2 - Vehicle parameters

The following vehicle characteristics may affect the stability of CWR track:

- Axle load, wheel base and bogie centres may affect both lateral bending of the track and the precessional uplift wave. The resistance to lateral displacement may be affected by the stiffness and mass of the track panel.
- The transverse forces (ΣY) generated by the vehicles should be less than the lateral resistance of the track in the loaded state in order to prevent displacement of the track under the moving train (for more information, refer to *UIC Leaflet 518*).
- Heating of the rails by, for example, eddy-current brakes may affect the stability of the track.

3.3 - Maintenance work

(See also point 5.3 - page 15).

Consolidation of the ballast will be necessary after tamping in order to restore the full lateral resistance of the track. This may be achieved naturally by the action of traffic or by other measures e.g. use of a dynamic track stabiliser.

During the period of reduced lateral resistance of the track, imposition of a temporary speed restriction may be necessary until the track is sufficiently stable, particularly when it is anticipated that high temperatures will occur immediately after tamping.

3.4 - Bridges

The following factors will affect the longitudinal forces in CWR track in the vicinity of bridges:

- changes in the track modulus adjacent to the bridge abutments,
- end rotation of the bridge as a result of the load imposed on the structure,
- changes in the length of the structure caused by temperature changes,
- longitudinal displacement of the structure caused by braking and acceleration.

UIC Leaflet 717 and *UIC Leaflet 774-3* provide advice on the effects of forces generated within bridge/ abutment transition zones, on the track alignment and the stability of CWR track. The leaflets also provide advice on the use of CWR track without expansion joints on bridges.

CWR should ideally be installed on bridges when the bridge itself is in a stress-free condition in order to minimise the effect of expansion of the bridge on the longitudinal forces in the rails.

Switches should not be located over bridge bearings.

Care should be taken to ensure that the presence of check rails or guard rails does not generate additional longitudinal forces in CWR track.

3.5 - Tunnels, gradients and braking

In locations where large or uneven changes in rail temperature are experienced, longitudinal movement of the sleepers in the ballast or of the rails relative to the sleepers may alter the original stress-free temperature of the track.

The effect will depend on the characteristics of the ballast, the type of sleeper or the creep resistance of the fastenings.

The longitudinal forces generated by vehicles may produce similar effects.

Such effects may occur particularly:

- in the vicinity of tunnel portals and in deep cuttings,
- on rising and falling gradients,
- in long continuous curves,
- on tracks where eddy-current brakes are in use.

In order to minimise the effect on the stress-free temperature and the consequential reduction in stability of CWR track, the above situations shall be subjected to particularly careful monitoring. Appropriate additional measures shall be taken to improve the stability of the track where this is considered necessary.

3.6 - Switches

The presence of additional rails of the diverted track can create increased longitudinal forces in switches particularly at, and in advance of the switch toe. The lateral resistance at these locations may be enhanced using anchoring devices or other measures.

3.7 - Variation of gauge

Variations in gauge have only a minor effect on track stability and can usually be ignored in this context.

4 - Installation of CWR track

4.1 - Preconditions

Whilst it is permissible to pass track maintenance machines or traffic under a speed restriction through a site during the construction period, when the ballast profile may not be complete, final fixation of the track and welding of the rails into CWR must not take place until the longitudinal and lateral resistance of the track frame is assured.

Stressing and final welding of the rails shall only be carried out once the specified vertical profile and lateral alignment of the track have been achieved and the required ballast profile has been installed.

4.2 - Initial temperature within the installation temperature range

If the initial temperature is within the installation temperature range with the rails in the unstressed condition (i.e. immediately after placing on the sleepers), the rails can be finally welded and fastened down without any special measures being required.

4.3 - Initial temperature below the installation temperature range

If the initial temperature is below the installation temperature range, final welding and fastening down shall only be carried out after the rails have been artificially lengthened by the application of heat or by the application of tensile force.

The required increase in length $\Delta\ell$ is calculated according to the following formula:

$$\Delta\ell = \alpha \times \ell \times \Delta t$$

where: $\Delta\ell$ = required increase in rail length

α = coefficient of expansion of the rail steel ($11{,}5 \times 10^{-6}$ °C)

ℓ = length of rail to be rendered stress-free

Δt = difference between installation temperature and initial temperature

This formula is only valid if the rails are free to expand. Therefore prior to stressing, the rail fastenings shall be loosened and appropriate measures taken to eliminate friction between the rails and sleepers.

The required extension shall be calculated and marked on the rail foot and adjacent sleeper.

Check marks shall also be made at appropriate positions within the anchor length against which the rails are to be stressed.

The rails shall then be lengthened by the application of heat or tensile force until the desired extension has been achieved, ensuring that the check marks on the anchor length have not moved during this process.

The final weld shall be made and after completion, the entire rail length shall be fastened down.

Further rail lengths may be subsequently dealt with in the same way.

4.4 - Initial temperature above the installation temperature range

In these circumstances, the rails should be temporarily installed at the initial temperature, and later, when the appropriate temperature range is achieved, the rails shall be adjusted in accordance with point 4.2 or point 4.3 - page 12, as appropriate.

4.5 - Measures to eliminate friction

Prior to stressing the rails, it is not sufficient simply to loosen the fastenings. The friction between rail foot and sleeper (or rail pad) must be eliminated by using rollers under the rail foot and additionally on curves, on the side of the rail head. The rails may also be vibrated using heavy plastic hammers.

4.6 - Stressing records

Records shall be kept of all stressing work undertaken, including on those occasions when the initial temperature range falls within the installation temperature range.

It is recommended that the stressing records contain the following details:

- location, mileage and direction of traffic,
- statement of completion of track-geometry marking and ballasting,
- details of stressing process including:
  - date and type of welding process,
  - stressing method,
  - installation temperature,
  - initial temperature,
  - initial rail length,
  - calculated rail extension,
  - name of person responsible for undertaking the work,
  - name of supervisor.

The records shall be maintained indefinitely or until updated at the next stressing operation on the same site.

5 - Maintenance

5.1 - General principles

Maintenance operations on CWR which affect rail stresses, track-panel stiffness, creep resistance or lateral resistance of the track, also impact on track stability. Consequently, operations of this type must only be undertaken within a limited range of rail temperatures.

In extreme situations, prior to undertaking work which may affect the stresses in the rail or reduce the lateral resistance of the track, i.e. ballast cleaning, sleeper replacement or significant changes to track geometry, a decision must be taken whether or not temporarily to convert the track back to jointed track.

5.2 - Range of temperatures within which work may be undertaken

5.2.1 - Installation temperature

The installation temperature determines the basis of the temperature range within which maintenance work may safely be undertaken. It is therefore important that this is known for each track section.

5.2.2 - Permissible range

Maintenance work which might affect track stability and rail stresses is only permissible within the following temperature range:

$$T_f - b \text{ and } T_f + a$$

5.2.3 - Limit values

The recommended values of "a" and "b" lie within the range 5 to 15°C and may be altered depending on the type of operation undertaken, the techniques used, the nature of the track, i.e. type of sleeper or curvature and the particular maintenance machine in use.

If it is necessary to carry out emergency work outside this temperature range, then special precautions must be imposed to ensure safety.

5.2.4 - Monitoring

The rail temperature shall be monitored and recorded during such maintenance operations, and the work must cease and all ballasting and tightening of fastenings must be completed before the limiting temperatures are reached.

5.3 - Measures to ensure track safety

5.3.1 - Change in lateral resistance

Work affecting the ballast can reduce the lateral resistance of the track to 40% of the value of consolidated track. Compaction of the ballast at sleeper ends can restore 5% to 10% of this reduction.

The initial lateral resistance is restored under the action of traffic. The use of a dynamic track stabiliser can restore the equivalent of 75 000 to 100 000 gross tons of traffic (metric tons). A significant proportion of the lateral resistance can be recovered after 100 000 to 200 000 gross tons of traffic, or after the equivalent consolidation achieved using a dynamic track stabiliser. The actual value achieved depends amongst other things on the type of sleepers and the maximum speed and axle-load of trains. The time taken to achieve full lateral resistance again after maintenance work is called the stabilisation period.

5.3.2 - Traffic speed during maintenance work

Maintenance work carried out on a track may reduce the ballast level and compaction on that or the adjacent track, and it may therefore be necessary to impose an appropriate speed restriction. The severity of the speed restriction will be determined by the extent of the work and the anticipated temperatures. Imposition of speed restrictions can cause disruption to traffic and their use should be minimised by avoiding maintenance work on CWR track during periods of extreme temperatures.

5.3.3 - Traffic speed after maintenance work

Following maintenance work, if the rail temperature exceeds $T_f + d$ before the stabilisation period has elapsed, a temporary speed restriction should be imposed. The value of "d" should be fixed by each railway after consideration of the climatic conditions and the nature of the track condition.

The speed restriction may be increased in stages depending on the sleeper type and traffic.

5.3.4 - Inspection

5.3.4.1 - Methods of inspection

CWR track may be inspected in a variety of ways including by foot patrols, from driving cabs or from the rear of trains, with track inspection coaches or by local measurement.

5.3.4.2 - Frequency

The frequency of inspection will depend on line speed, the volume of traffic, and the type and condition of the track.

5.3.4.3 - Inspection details

When inspecting CWR track, particular attention should be paid to:

- the completeness of the ballast,
- the alignment, both vertically and laterally,
- the integrity of the fastenings,

- the completeness of any anti-creep devices or other anchorages,

- the appropriate operating speed.

Particular attention should be paid to track sections which are subjected to different levels of exposure to sunshine during the day, including in cuttings, in front of tunnel portals and on steep gradients, as these may be particularly prone to longitudinal movement.

If it is suspected that longitudinal movement of the rail is occurring, measurements should be instigated.

Particular attention should also be paid to special track features such as:

- switches and crossings,

- level crossings,

- bridges with direct fastenings or slab track,

- bridge bearings or expansion joints.

6 - Elimination of problems

6.1 - Rail breaks

Three options are available for the repair of broken rails:

- immediate actions,
- temporary repair,
- permanent repair.

The first two steps may be the same, or only a permanent repair may be undertaken.

6.1.1 - Immediate actions

The immediate actions on finding a broken rail in CWR track are to fit emergency fishplates around the break and, if necessary, provide support to the rail by means of a block. Depending on the type of break it may be necessary to impose a temporary speed restriction. In addition the rail fastenings should be checked and, if necessary, tightened over a distance of at least 30 m. If tightening of the rail fastenings is not sufficient to restrain the rail, then, in cold climatic conditions, a sufficient number of anti-creep devices should be placed on each side of the break to limit longitudinal movement. In hot weather, it may be necessary to cut a joint in the adjacent rail.

6.1.2 - Temporary repair

A temporary repair requires all the work necessary to allow resumption of normal train operations to be carried out, except for final welding.

It may be necessary to instal a replacement rail fishplated to the existing track. The minimum length of the replacement rail must be specified by each railway and may depend on line speed. The gap created by the break shall be measured so that eventually the original length can be restored and the correct stress condition obtained. It is recommended that one end of the replacement rail shall be welded in to the existing track, as soon as possible.

6.1.3 - Permanent repair

Different methods can be used to effect a permanent repair but these must always result in a known stress condition being restored.

6.1.3.1 - Welding existing rail after marking

If the break is clean and the existing rail can be re-welded, a punch mark should be made on the side of the rail head 1 000 mm each side of the edge of the break, the welding gap cut and the rails extended to ensure the distance between the two marks is exactly 2 000 mm. The rails should then be welded using a wide-gap thermit weld if necessary.

6.1.3.2 - Welding replacement rail after marking

If it is decided to replace the broken rail, the gap created by the break must first be measured. Telltale marks should be marked on the rail and sleeper outside the limits of the proposed replacement rail length. The existing broken rail should then be cut out, and the replacement rail welded in at one end. The replacement rail should be extended by the length of the original gap created by the break and welded, using a normal thermit weld.

6.1.3.3 - Welding existing or replacement rail without marking

If for any reason the gap created by the break is not known, then the rails must be stressed in the normal manner (see point 4 - page 12) irrespective of whether the existing rail or a replacement rail is used.

6.2 - Track buckling and distortion caused by heat

Track buckling or distortion occurs when the heat-induced compressive forces in the rails are sufficient to overcome the lateral resistance of the track structure.

The wavelength of a buckle is typically 8 to 20 metres with an amplitude of up to 1 000 mm or more.

The wavelength of a distortion is typically 4 to 8 metres with an amplitude of 20 to 80 mm.

6.2.1 - Operating measures

Following the occurrence of a buckle or distortion, the track must be closed to traffic. On re-opening it may be necessary to impose a temporary speed restriction because of misalignment of the track or the existence of track defects caused by the buckle.

6.2.2 - Temporary restoration of the track

The cause of the buckle should be established before remedial work is undertaken.

The track must be restored to its original condition.

It may be necessary to cut both rails, remove excess rail and temporarily fishplate them together.

It may be necessary to free off the fastenings over the affected zone and then re-tighten them.

Any badly distorted rails and damaged sleepers must be replaced.

The affected zone should be liberally ballasted, tamped and re-aligned, and then compacted if necessary.

A temporary speed restriction should be imposed and the behaviour of the track should be monitored.

6.2.3 - Final restoration of the track

Following a track buckle or distortion, the track shall be re-stressed in the normal way including the lengths of track abutting the buckle zone.

If necessary during very hot weather when it is considered that there is a risk of further buckling occurring at the same location, the rails may be stressed to a higher stress-free temperature than normal, then re-stressed at a later date to the normal stress-free temperature once colder conditions prevail.

Appendix A - Safety

A.1 - Safety fundamentals / philosophy

The basic premise for CWR buckling safety assurance lies in the performance-based requirement (statement) that "CWR track shall have the buckling strength required to withstand the environmentally and operationally imposed loads for the range of expected operating conditions". The translation of this statement into viable and *usable* safety specifications requires a rational CWR buckling safety management methodology based on application of the following four key elements:

- CWR track system / component characterisation,
- Conduct buckling / stability analyses,
- Establish and apply safety criteria,
- Perform safety evaluation

The first element requires the track to be defined in terms of its governing parameters, specifically the rail properties, track curvature, lateral, longitudinal and torsional resistance of the track, permissible track misalignments, sleeper/ballast friction coefficient, track modulus, and vehicle characteristics and loads.

The second element requires the application of a dynamic or "quasi-dynamic" buckling analysis/model which appropriately incorporates all the governing track parameters above, and **correctly** predicts the critical buckling forces and temperatures for the determination of the buckling response characteristics.

The third element establishes buckling safety criteria based on an appropriate stability criterion applied to the analytically determined buckling response curves for the "*levels of safety*" desired.

The last element requires applying the safety criteria either:

- to perform a buckling safety evaluation and "reserve buckling strength" (margin of safety) determination directly, as in the US DOT's "CWR-BUCKLE" model (see Bibliography - page 43), or,
- to develop safety guidelines / specifications in terms of "allowable temperature increase" limits as functions of track parameters / conditions, and apply these specifications for safety assessments.

In the first case, the safety assessments are conducted through direct application of the safety analysis model, while in the second, the model is used to establish a set of parametric safety envelopes, which can be used as safety guidelines.

In the following, it will be assumed that the first two elements of the buckling safety management methodology are readily available, as in "CWR-BUCKLE", hence the discussion will be limited to the safety criteria and safety analysis parts. Both deterministic and probabilistic approaches will be presented.

A.2 - Safety concepts and criteria

The general theory of CWR track buckling and safety concepts is available in "*Dynamic Bucking of CWR Track: Theory, Tests and Safety Concepts*", "*Parametric Analysis and Safety Concepts of CWR Track Buckling*" and "*Theory of CWR Track Stability*" (see Bibliography - page 43). This theory, together with the appropriate safety criteria, has been incorporated into a buckling safety analysis model "CWR-BUCKLE" (see Bibliography - page 43) which has undergone rigorous test validations. A general purpose analysis code for track and bridge stability and deflection evaluations called "CWERRI" (see Bibliography - page 43) is also available for buckling analyses, although without safety criteria. These models predict the buckling response characteristics, based on which safety concepts can be developed. Consistent with the buckling safety assurance statement in point A.1 - page 20, the starting point is to require an "allowable or permissible temperature increase", T_{all}, *which should be larger than the anticipated maximum rail temperature increase referenced to the stress-free temperature*, ie:

$$T_{all} > (T_{max} - T_n)$$

T_{all} can be considered as the "**required buckling strength**" which is dependent on the governing track and vehicle parameters discussed above. T_{all} can be derived by applying an appropriate stability criterion to the analytically-determined buckling response curves, or it can be empirically determined by dynamic buckling tests.

It should be noted that the stress-free temperature T_n is not the installation or fastening temperature, T_f, but the actual value in the service life of CWR which is *usually different due to changes induced by rail / track kinematics and maintenance actions*. In the absence of non-destructive techniques to determine T_n, a "safety factor" is usually established to account for the stress-free temperature variation. The stress-free temperature is then given as:

$$T_n = T_f - SFTN$$

where T_f is the rail fastening or installation temperature, and SFTN is the stress-free temperature variation safety factor. *For UIC tracks, the recommended values for SFTN are in the range of 5-10°C*.

A.2.1 - Basis for Determination of Allowable Temperature

The (correctly predicted) buckling response curves provide the basis for the allowable temperature T_{all} (see Figure 1 - page 28 for illustration). These equilibrium curves are characterised by an upper and lower temperature (increase) value, and buckling can take place in between these two temperatures. The allowable temperature can be based on either the Lower Critical Temperature $T_{b,min}$ or on a temperature above $T_{b,min}$ (but less than $T_{b,max}$) depending on the "*levels of safety*" desired, i.e.:

- Level 1 Safety: $T_{all} = T_{b,min}$
- Level 2 Safety: $T_{all} = T_{b,min} + \Delta T$

NB : Level 1 tends to be more conservative, i.e. "safer" than Level 2, and the ΔT value is to be determined based on safety considerations.

Level 1 Safety based on $T_{b,min}$

The use of the lower critical temperature, $T_{b,min}$, as a baseline for allowable temperature is based on the fact that it "guarantees" (although not absolutely) the safety of CWR track against buckling, since only above this temperature do there exist possible buckled configurations (i.e. non-zero equilibrium states). Hence only above this temperature can buckling occur. Research has shown that at this lower critical temperature the buckling energy (i.e. energy required to displace the track into a buckled configuration) is "considerable", hence the T_{all} is fairly conservative, thus providing a "high" level of safety. It should also be noted that since the influences of the more complex train dynamics loads, such as braking and traction forces, impact loads, and localised thermal load inputs due to wheel flanging, are not included in the buckling models, this choice for T_{all} provides some added margin of safety against these dynamic effects (i.e. these dynamic effects are indirectly accounted for by the large buckling energies required to buckle the track at this temperature). Additionally, it should also be noted that an implicit assumption in this criterion is that the difference between $T_{b,max}$ and $T_{b,min}$ is larger than 20°C. This caveat (or sufficient condition) is required because buckling energy computations show that buckling energy values at $T_{b,min}$ decrease substantially as these two values approach each other, hence they may not be adequate to handle the aforementioned dynamic effects. It can be shown that most European track conditions and parameters tend to fulfil this requirement of $(T_{b,max} - T_{b,min}) > 20°C$. Note also that as shown in "*Theory of CWR track stability*" (see Bibliography - page 43), the choice of $T_{b,max}$ for T_{all} is prohibitive.

NB : For track structures and operating conditions which might require more stringent safety assurance, such as in heavy-haul freight territories with large train dynamics loads, and for "weak" track conditions (very low lateral resistance, large misalignments, and small radius curves) which result in $0 < (T_{b,max} - T_{b,min}) < 5°C$, T_{all} may need to be "adjusted downward" by a safety factor ΔT_1 to provide the required margin of safety. Based on current research data, a reasonable value for ΔT_1 may be set at 5°C, so that for these conditions the recommended safety criterion is:

$$T_{all} = T_{b,\,min} - 5°C$$

Level 2 Safety based on $T_{b,min} + \Delta T$

If a less conservative safety criterion is desired, T_{all} may be dependent on each railway organisation's ability to maintain tracks within desired tolerances, and to control operating conditions within "acceptable dynamic load" regimes, T_{all} may be increased to above Level 1 values by a factor ΔT. The choice or determination of ΔT is not trivial because buckling potential increases rapidly with temperatures above the $T_{b,min}$ value. This is based on research which shows that the buckling energy decreases sharply from a maximum value at $T_{b,min}$ to zero at $T_{b,max}$ (refer to Figure 2 - page 29 for illustration of buckling energy decrease as a function of temperature above $T_{b,min}$).

Approach 1 for ΔT determination

In this approach, the buckling energy versus temperature-increase relationship is used as a criterion for the choice of ΔT, i.e. Level 2 Safety is based on an allowable temperature corresponding to *a temperature at which there exists a finite buckling energy larger than zero, but less than the maximum value at* $T_{b,min}$, i.e.:

$T_{all} = T(\gamma E_{max})$, where $0 < \gamma \leq 1$, and E_{max} is the buckling energy at $T_{b,min}$.

Hence for the special case when $\gamma = 1$, $T_{all} = T(E_{max}) = T_{b,min}$, and Level 2 Safety becomes equal to Level 1 Safety. The value of γ is to be determined analytically and experimentally, and the Level 2 Safety based on it must be validated through full-scale dynamic buckling tests. Research to date - "*Dynamic Buckling of CWR Track: Theory, Tests and Safety Concepts*" (see Bibliography - page 43) - suggests a value of $\gamma = 0{,}5$, **referred to as the *50% Buckling Energy Level***, so that the allowable temperature for Level 2 Safety is the temperature above $T_{b,min}$ which corresponds to the 50% Buckling Energy Temperature (50% BET), or $\mathbf{T_{all} = T(0{,}5E_{max}) = 50\%\ BET}$. Based on this buckling energy concept then: $\mathbf{\Delta T = 50\%\ BET\text{-}T_{b,min}}$.

Approach 2 for ΔT determination

If the CWR-BUCKLE model is not available for the determination of buckling energies, an alternative definition of ΔT may be based on model prediction of $T_{b,max}$ and $T_{b,min}$, specifically: $\mathbf{\Delta T = 0{,}25(T_{b,max} - T_{b,min})}$. This choice is based on *ERRI Committee D 202* parametric studies employing CWERRI and CWR-BUCKLE, which show close equivalence of the two approaches.

CAUTION: When employing any safety criteria based on $T_{b,max}$, special attention must be paid to the accuracy of the buckling model to predict $T_{b,max}$ and on the extreme sensitivity of $T_{b,max}$ on the governing parameters - "*Parametric Analysis and Safety concepts of CWR Track Buckling*" (see Bibliography - page 43).

A.2.2 - Applications of Level 1 and Level 2 Safety Limits

NB : Level 1 Safety **should** be used when $5°C \leq (T_{b,max} - T_{b,min}) \leq 20°C$, while Level 2 Safety may be used when $(T_{b,max} - T_{b,min}) > 20°C$. For the special cases when $0 < (T_{b,max} - T_{b,min}) < 5°C$, the criterion of $T_{all} = T_{b,min} - 5°C$ is recommended. Track conditions resulting in progressive buckling, i.e. when the buckling response does not exhibit distinct T_b values, should not be permitted.

A.3 - Safety Evaluation and Safety Limit Charts

As indicated in point A.1 - page 20, the buckling safety evaluation can be performed either directly, by a PC-based buckling safety analysis software using the appropriate T_{all} safety criteria, or through application of safety-limit charts which give the safe allowable temperatures for a set of prescribed track conditions. This requires testing the buckling model a-priori for the many cases of parametric variations. From a practical point of view, it is desirable to reduce the number of parameters to the primary group of:

- rail size,

- lateral resistance,

- misalignment,

- curvature,
- fastening torsional resistance,
- rail stress-free temperature.

All other (secondary) parameters may be "suppressed" by setting them at their nominal values as discussed in "*Dynamic Buckling of CWR Track: Theory, Tests and Safety Concepts*", "*Parametric Analysis and Safety Concepts of CWR Track Buckling*" and "*Theory of CWR Track Stability*" (see Bibliography - page 43). The primary parameters have a significant influence on the upper and lower buckling temperatures, and they are also the parameters to control for buckling safety. For cases when these secondary parameters are significantly different from the assumed nominal values, then direct application of the computer model is required for an exact evaluation of the buckling temperatures and safety. Figure 3 - page 30 provides an example of safety limits in terms of T_{all} versus lateral resistance for a range of track curvatures, and an example of an application to evaluate safety.

A.4 - CWR Buckling Safety Based on Risk Methodology - Extension to risk-based safety assessment

There is always some degree of buckling risk in field conditions, owing to the variability of track parameters which can significantly influence the CWR buckling potential. Thus, even though the requirement of $T_{all} > (T_{max} - T_n)$ is satisfied for the majority of track conditions, on occasions an unexpected reduction in lateral resistance, stress-free temperature, or an unanticipated high rail temperature can result in T_{all}, being exceeded, and buckling can then occur. In these situations, the evaluation of the probability of buckling failure for CWR track in terms of risk severity is required. Such risk assessments can be used to compute a "reliability index" or a "buckling risk index" (BRI) which indicates the degree of safety of CWR tracks in a probabilistic sense.

A.4.1 - Risk Assessment Approach

Existing buckling safety analysis models such as "CWR-BUCKLE" and CWERRI programs predict the upper and lower critical temperature increases, and the safe allowable temperature increase values for given user input parameters. These parameters are at present considered to be deterministic inputs by the user, whereas it is well known that in field conditions, some of the parameters will vary over a considerable range. Salient parameters are lateral resistance, misalignment and the rail stress-free temperature. Knowing the frequency distributions of these parameters, one can determine *the probability of track buckling or a "risk severity index"* through risk analysis. Risk analysis is important because:

1. the track cannot be designed, maintained and operated for every possible scenario of its parameters, nor for the worst-case situations, and
2. there is always some finite probability associated with some of the user inputs, especially in the absence of reliable (and real time) measurements.

The risk assessment of CWR track buckling can be based on known (measured) or assumed (experience-based) distributions of the key parameters referred to above, and on the buckling criterion presented in point A.2 - page 21, namely:

$$\chi = T_{all} - (T_{max} - T_n)$$

If $\chi \leq 0$, then buckling will occur. Thus, the probability of χ becoming zero or less needs to be evaluated. Figure 4 - page 31 illustrates the process based on a set of assumed probability distributions of lateral resistance (F_p), misalignment (δ_0), and stress-free temperature (T_n). For chosen combinations of (δ_0), (F_p) and (T_n), the resulting values of χ can be computed using the buckling model for a given maximum rail temperature, T_{max}.

A.4.2 - Definition of "Buckling Risk Index" (BRI)

A risk index for buckling can be defined for the given distributions based on the percent failure ratio, or:

Buckling Risk Index (BRI) = n/N

where N is the total number of cases considered (5 x 5 x 3 = 75 for the illustration in Figure 4) and n is the number of cases for which $\chi \leq 0$ for a given T_{max}. This can be plotted as a risk severity curve, i.e. buckling risk index versus maximum rail temperature as illustrated in Figure 4.

A.4.3 - Buckling Safety Based on Risk Severity (Risk Acceptance)

Each operator must then determine his own acceptable level of risk (i.e. 0%, 5%, 10%, etc.), based on specific operating conditions and maintenance practices. ***Or alternatively, maintenance practices can be based on the "uniformity" of parameters required for a defined risk level***. For the case presented in the illustrative example, if "absolute safety" is required, i.e. 0% risk, then for the track conditions characterised by the given frequency distributions, the maximum rail temperature permitted is 50°C.

A.5 - Special Track Equipment: Switches, Turnouts and Approaches to Bridges

In principle, the above approaches for the assurance of lateral stability for conventional CWR tracks are also applicable to special situations such as switches, turnouts and bridge approaches. However, the development of applicable safety criteria is awaiting the results of current research work on theoretical model developments, verification studies, and data on the governing parameters required for strength, stability and failure evaluations.

A.6 - Safety Criteria for High-Speed Applications: Track Lateral Shift

The criteria for CWR buckling safety developed above apply to all tracks. However, due to the high tolerance requirements for track geometry, to the generally more stringent requirements for track strength, and to a better control of rail stress-free temperature variation, high-speed track safety is usually assured from the buckling point of view. The lateral stability issue affecting high-speed track safety, however, is *the formation and growth of lateral track misalignments due to the high ratio of Lateral to Vertical (Y/Q) loads and longitudinal forces*, ***or what is defined as track lateral shift***. The distinction between track lateral shift and track buckling as parts of the overall track stability mechanism is made in Figure 5 - page 32. The resulting lateral misalignments caused by track shift tend to be "small" in magnitude but, in combination with other parameters, can lead to unsafe conditions of wheel climb, dynamic wide gauge, bogie hunting, track buckling, or to conditions leading to unacceptable ride quality.

Hence the safety issue for high-speed track is the determination of "critical misalignment" δ_c at which high-speed operation becomes unsafe.

A.6.1 - Track Lateral Shift Mechanism, Parameters and Allowable Misalignments

Figure 6 - page 33 illustrates the fundamentals of track shift as a "moving load problem" in terms of the number of axle passes required to produce a permanent (residual) deflection, which may be either stable (as shown by δ_1 and δ_2) or unstable (i.e. progressively increasing with the number of passes). The key influencing parameters are also identified. For high-speed track operations, three levels of lateral misalignment are typically defined:

- initial misalignment after construction or realignment, δ_0,
- maximum allowable "pre-maintenance" misalignment, δ_m,
- critical misalignment at which operations are impacted and safety is potentially compromised, δ_c.

The initial misalignment after re-alignment or construction tolerance for new tracks is represented by δ_0. This misalignment is typically of the order of one to four millimeters for high-speed tracks. The maximum allowable misalignment prior to maintenance operations according to individual railway practices is represented by δ_m and may be in the range of 4-8 mm. The critical misalignment amplitude at which vehicle operational safety is impacted is represented by δ_c. Several possible "failure modes" and/or design requirements may have to be considered to determine the lowest value of δ_c. These include sudden track shift potential, wheel climb, rail roll, buckling, inadequate ride quality, and exceedance of vehicle design loads.

Displacements δ_1 and δ_2 are stable deflections at a number of passes, and are reached (or allowed) only if δ_c is larger than these. For some high-speed track conditions and parameters, stabilisation may not be reached prior to δ_c, hence the determination of δ_c for high-speed tracks is a key requirement for the development of applicable safety criteria. This critical misalignment δ_c can be determined from mechanistic considerations for given vehicle parameters, speed, track conditions, lateral resistance characteristics and thermal loads, based on vehicle/track dynamics model predictions of the Y/Q loads. These Y/Q loads are then used as input into a "moving load" track lateral response model for the determination of the residual deflections under many axle passes.

The pre-maintenance misalignment δ_m can be determined on a trade-off basis between the frequency of maintenance (number of safe vehicle passes or MGT) and the margin of safety based on critical misalignment δ_c. The construction tolerance δ_0 is usually determined by the railways as a trade-off between the cost of construction (tolerance and quality assurance), maintenance and the number of passes that can be obtained between maintenance cycles.

A.6.2 - Track Shift Criterion for High-Quality Tracks

In line with the above, requirements imposed by high-speed operating conditions, on permissible misalignments dictate "allowables" to be determined based on track shift considerations, more specifically in terms of prescriptions based on δ_0, δ_m and δ_c. The safety criteria for limiting track shift to acceptable values can be stated as the following:

- High-speed tracks under maximum expected vehicle and thermal loads should have a minimum lateral strength to limit the development of lateral misalignments to within a specified value: $\delta_L \leq \delta_c$, or alternatively,

- Lateral loads generated by high-speed vehicles operating under maximum speed, cant deficiency, thermal load, and initial misalignment conditions should not cause the exceedance of an *allowable* deflection limit: $\delta_L \leq \delta_c$.

  The quantification of this criterion in terms of permissible net axle-loading (NAL/V) ratios when the "allowable" deflection limit is based on the track lateral yield strength (or elastic limit) of $\delta_L \leq 1$ mm is available in "*Recent Investigations on Track Lateral Shift Limits For High-Speed Rail Applications*" (see Bibliography - page 43). Depending on the specific high-speed track parameters and vehicle characteristics, these permissible net axle-load ratios fall in the range of NAL/V = 0,4 - 0,6. The key influencing parameters are the track lateral resistance characteristics, sleeper/ballast friction coefficient, vehicle vertical axle-load, track curvature, thermal loads, and constant versus variable, lateral axle-loads - "*Fundamentals of Track Lateral Shift For High Speed Rail Applications*" (see Bibliography - page 43).

A.7 - Figures

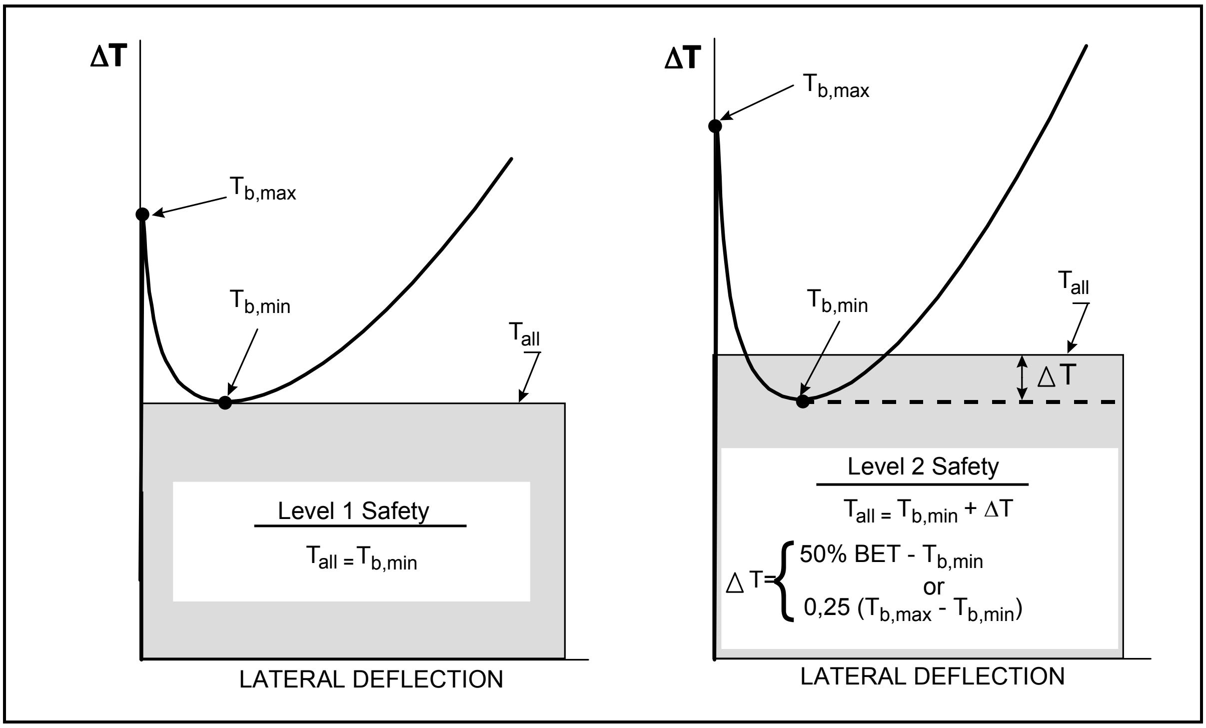
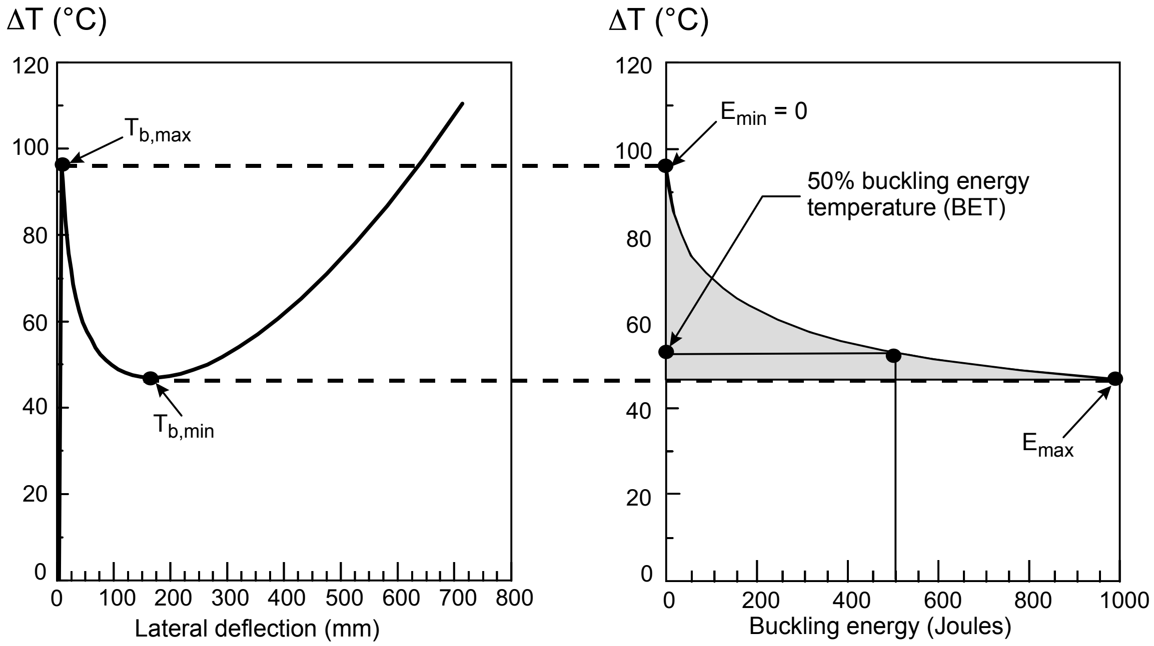


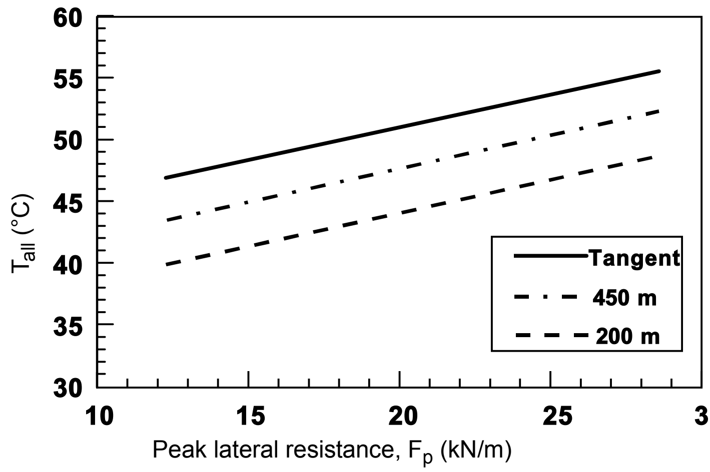
Fig. 1 - Safety criteria definition in terms of "allowable temperature increase" for safety levels 1 and 2



Parameters

Rail: UIC 60	Sleeper type: concrete
Misalignment: 12 mm in 8 m	R = 300 m
Torsional resistance: medium	Longitudinal resistance: medium
Axle loads: UIC/D4	

Fig. 2 - Buckling energy concept illustration



Parameters

Rail: UIC 60
Misalignment: 12 mm in 8 m
Torsional resistance: medium

Axle loads: UIC/D4
Sleeper type: concrete
Longitudinal resistance: medium

NB: Estimates on lateral resistance ranges:

- Tamped to 0,2 MGT $\cong$ 12-18 kN/m
- Stabilized (0,2 to 1 MGT) $\cong$ 19-22 kN/m
- Consolidated $\cong$ 23-28 kN/m

Buckling Safety Evaluation

Safety Criterion: $\chi = T_{all} - (T_{max} - T_n) \geq 0$

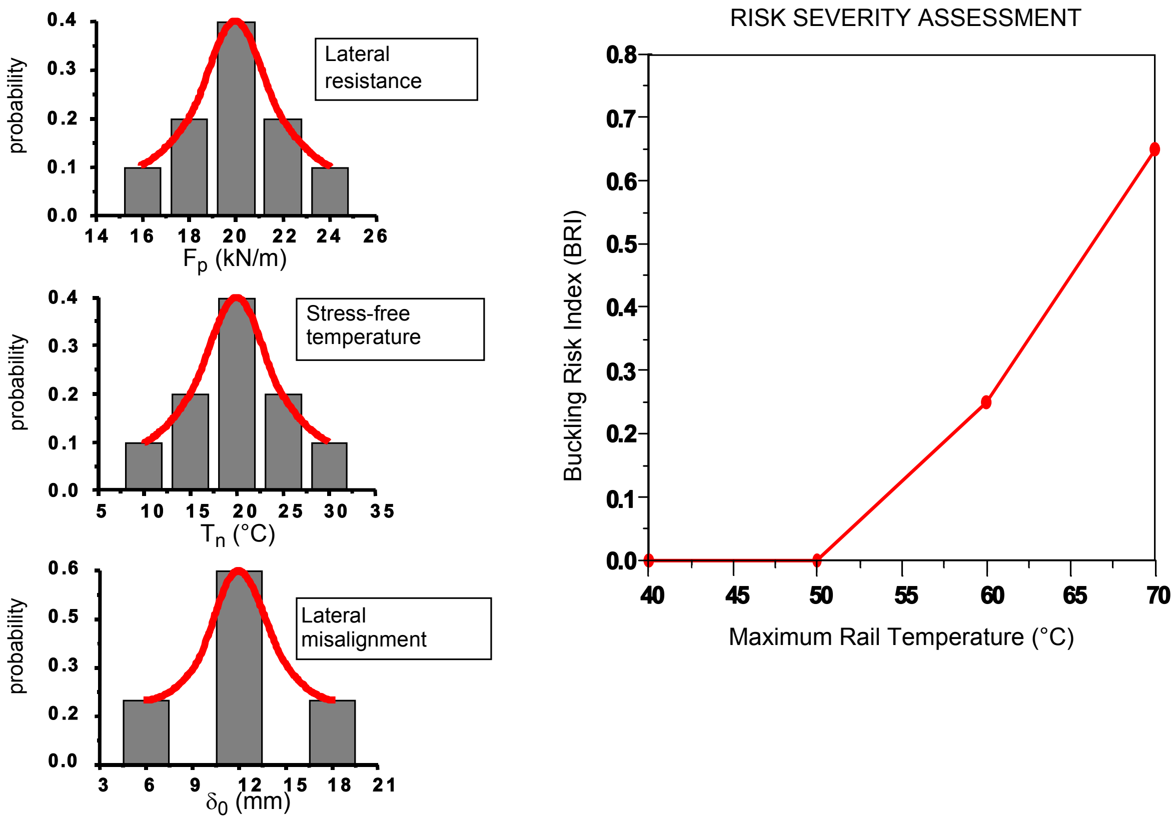
where:

T_{max} = maximum rail temperature
T_n = stress-free temperature = fastening temperature - SFTN
SFTN = safety factor for T_n variation $\cong$ 5°C

Example: For a weak (tamped) R = 450 m track fastened at T_f = 20°C, and assuming a 12 mm line defect, what is the permissible T_{max} ?

Answer: Determine $F_p \cong 15$ kN/m;
then, from figure: T_{all} = 45°C ;
then, $\chi = 45 - (T_{max} - 15) \geq 0$
T_{max} (permissible) = 60°C

Fig. 3 - Buckling safety limits for CWR tracks based on Level 1 safety criterion



Parameters

Rail: UIC 60	Longitudinal resistance: medium
Sleeper type: concrete	Vertical modulus: 41 Mpa
Radius: 300 m	Axle loads: UIC/D4
Torsional resistance: medium	

Fig. 4 - Buckling safety based on risk severity assessment

Stage	Event	Cause	Result
1	Formation of initial line defects ("small")	(1) Initial imperfections (welds) and construction defects (2) High Y/Q's due to bogie hunting (3) Localized weak ballast conditions (4) Longitudinal forces	Lateral misalignment
2	Growth of misalignments ("small" to "moderate")	(1) Net axle Y/Q increase due to line defects (2) High Y/Q's due to bogie hunting (3) High longitudinal forces due to ΔT (4) Multiple wheel passes	Track lateral shift
3	Sudden formation of "large" misalignments	(1) High longitudinal force (2) Reduced T_n (stress-free temperature) (3) Misalignments generated by track shift (4) Dynamic uplift wave (5) Weakened lateral resistance	Track buckling

Fig. 5 - Track lateral-stability mechanism description

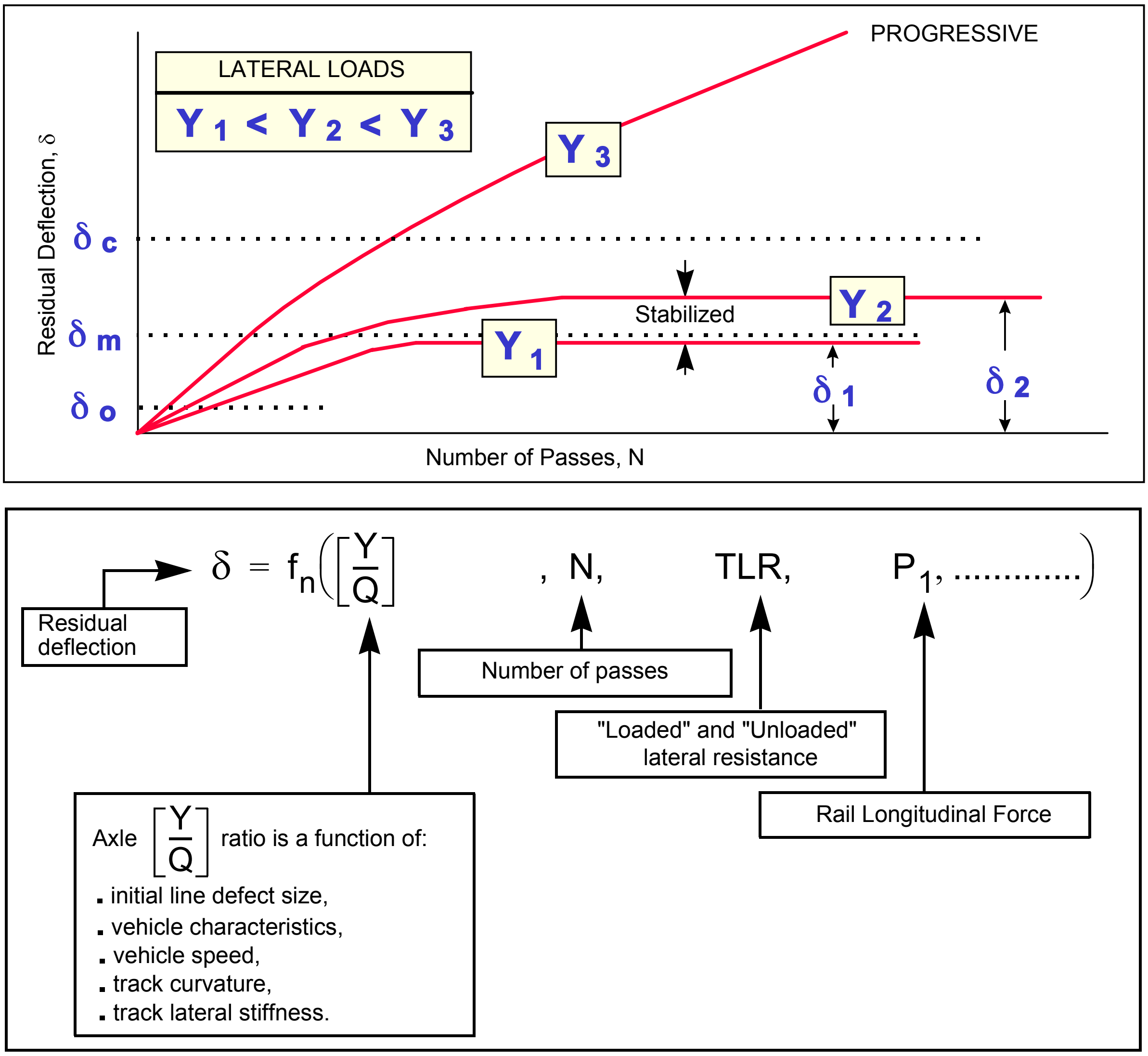


Fig. 6 - Track shift mechanism and key influencing parameters

Appendix B - Case studies

B.1 - Use of CWERRI and CWR-BUCKLE Models

Appendix A - page 20 defines track safety regarding buckling and the philosophy behind this. Under the auspices of ERRI Committee D 202 (see Bibliography - page 43) TU Delft developed CWERRI to assess track buckling quantitatively. It allows the longitudinal, vertical and lateral behaviour of CWR track to be modelled and calculated integrally in a user-friendly environment. The basic features of the *"Stability of CWR track"* model (see Bibliography - page 43) are as follows:

- three-dimensional modelling and calculation tool,
- longitudinal, lateral and vertical forces,
- lateral and vertical track stability - *"Theory of CWR track stability"* (see Bibliography - page 43),
- thermal and mechanical loads,
- complete train loads, taking uplift waves into account,
- three-dimensional ballast yield, taking the influence of vertical loads into account,
- track/bridge interaction, including the effects of end rotation,
- multi-span bridges with parallel tracks.

A major application of CWERRI is its use as a tool for safety analyses. Together with the DOT's CWR-BUCKLE program, a large number of calculations have been performed in developing the safety criteria implemented in this leaflet.

The results of the calculations with CWERRI are expressed in terms of the temperature of the rail above the normal or stress-free temperature. Normally, there is an area between two limits ($T_{b,min}$ and $T_{b,max}$) wherein buckling may occur.

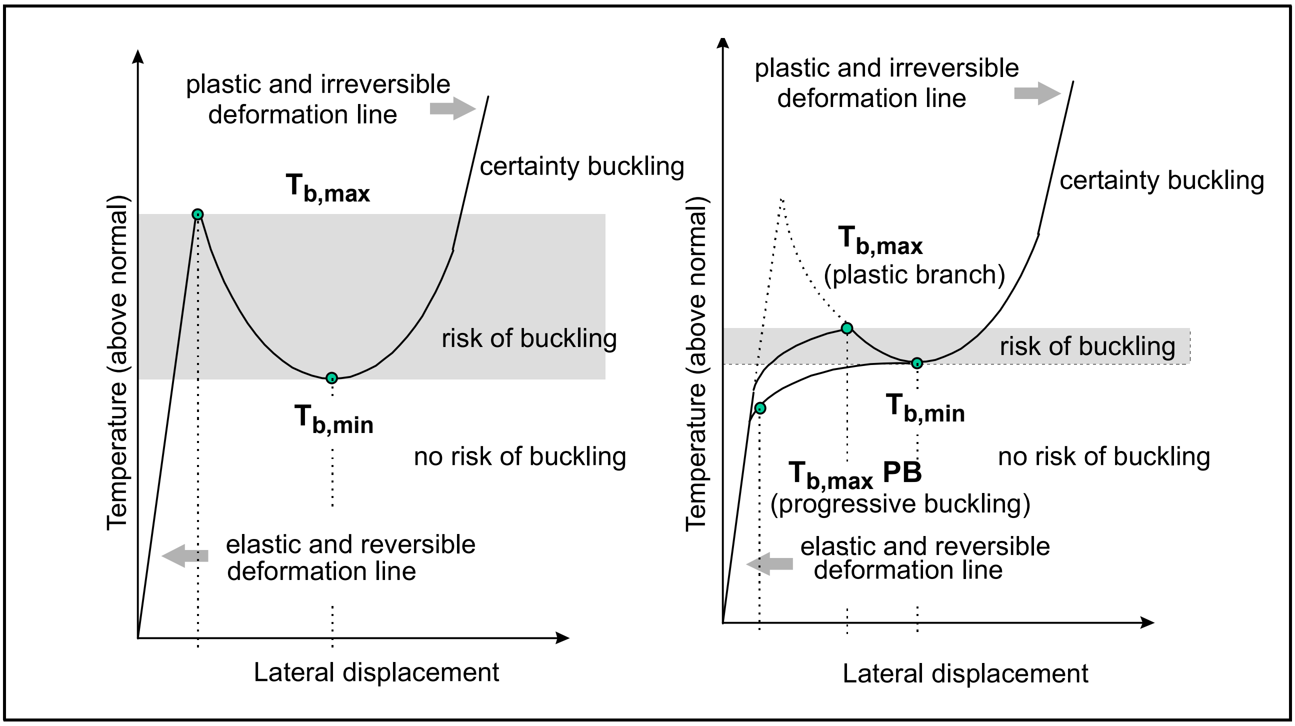


Fig. 7 - Temperature vs. lateral displacement for good ballast (left) and poor ballast (right)

It is widely assumed that track buckling in this area between $T_{b,min}$ and $T_{b,max}$ depends on the external addition of energy to the track, e.g. by a moving train when the track is in a "ready-to-buckle" condition. For temperatures close to $T_{b,min}$, the amount of energy is much larger than for temperatures close to $T_{b,max}$.

This amount can be calculated by a program called CWR-BUCKLE which was developed in the USA: *"Parametric analysis and safety concepts of CWR Buckling"* (see Bibliography - page 43) for the same purpose as CWERRI: track safety against buckling.

The parametric studies on track buckling - *"Parametric study and sensitive analysis of CWERRI"* *(see Bibliography - page 43)* - were carried out for the following four types of structures with both programs:

High-speed track:	design speed > 200 km/h
Main-line track:	design speed ≥ 160 km/h
Secondary-line track:	design speed ≥ 120 km/h
Freight-line track:	design speed ≥ 80 km/h

Each type of structure has its specific properties in terms of curve radii, sleeper type, ballast, fastenings and misalignments (as a result of maintenance specifications) and railway vehicles passing over it. Design speeds have only been added to indicate and classify track structures. The main results are summarised below in two examples.

B.2 - Example 1: High-speed and main-line tracks

In both track structures, an ICE trainset was used for the calculations. Compared to other high-speed vehicles, the ICE power car causes minimum total rail deflection between the two inner axles. This makes the track structure sensitive to lateral buckling. Calculations have been performed with UIC 60 rails and a vertical track stiffness of 100 MN/m/m'.

Different track properties are represented:

Structure type and number	Curve radius (mm)	Sleepers (tan φ)	Lateral ballast resistance (kN/m')	Torsional resistance of fastening (kNm/rad/m')	Misalignment (mm)
High-speed track (1)	Tangent	Concrete friction 0,86	10/10, 15/12, 20/16	75, 150	8/12/16
Main-line track (2)	900	Concrete friction 0,86	10/10, 15/12, 20/16	75, 150	10/14/18
Main-line track (3)	900	Wooden friction 1,2	7/7, 10/10, 15/12	150, 250	10/14/18

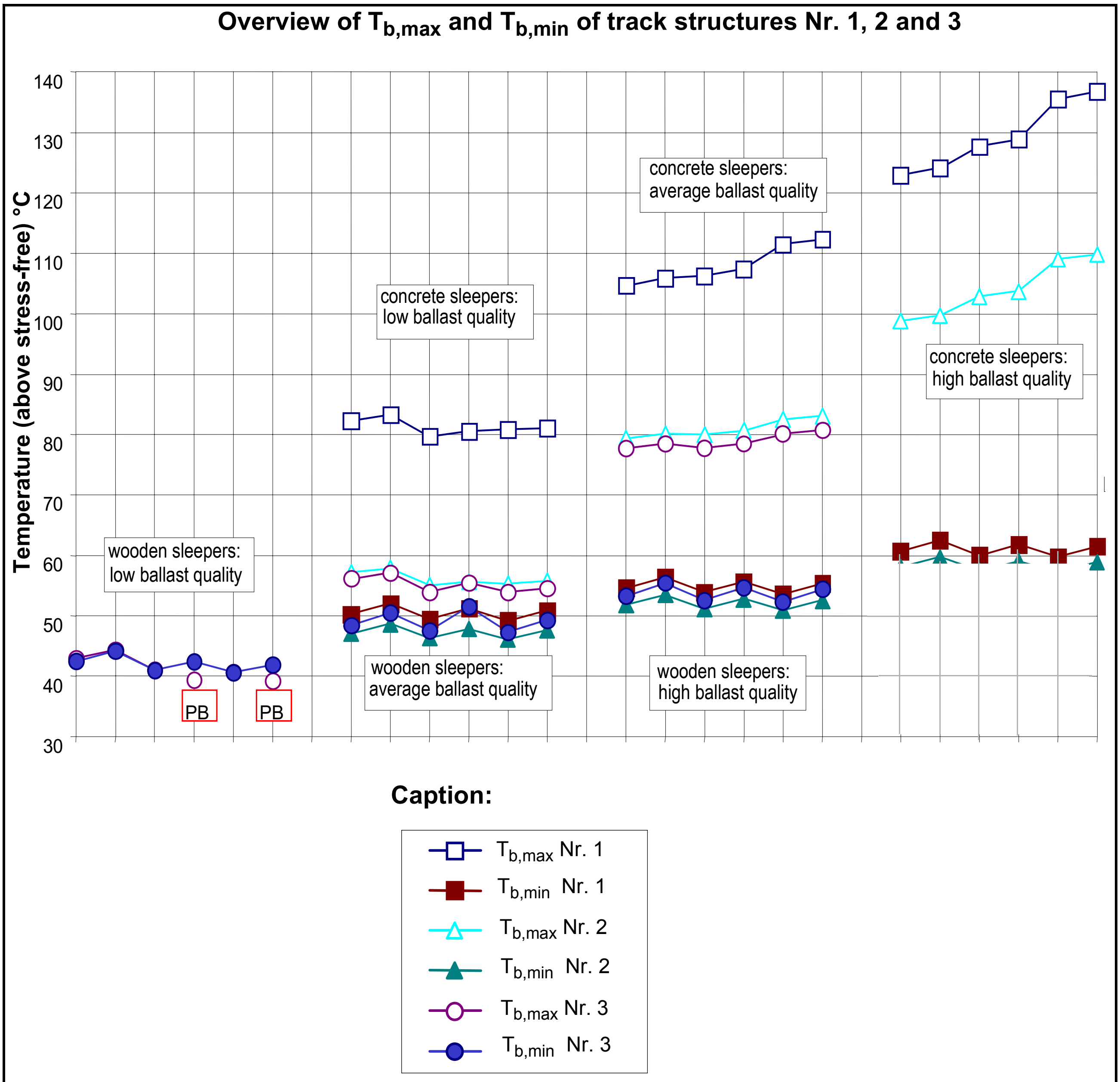
Observations concerning properties and values:

1. Concrete and wooden sleepers have different properties in terms of lateral resistance and interaction with ballast material. With wooden sleepers, ballast grains penetrate and increase lateral stiffness (represented by tan φ values). On the other hand, wooden sleepers are generally laid in lower qualities of ballast and wooden sleepers weigh less. These two factors reduce lateral stiffness.

2. Ballast material is characterised by two values: F_p and F_1. The first (higher) value indicates the maximum lateral force to be applied on a one metre track panel, causing an elastic lateral displacement (generally between 2 and 5 mm). The second value represents a constant (asymptotic) force value for friction of a track panel through and over the ballast grains.

3. Misalignments are in the lateral direction. The above mentioned values are magnitudes (double amplitudes) of a cosine shaped wave, respectively 8, 10 and 12 metres in length.

4. Torsional resistance varies with fastening type. It is commonly found that wooden sleepers show higher resistance than concrete sleepers. The influence on the results is, however, quite small.



NB: For each ballast quality, two alternatives are shown with increasing torsional stiffness and three alternatives with increasing misalignment length and amplitude.

Fig. 8 - CWERRI temperature results for high-speed and main-line tracks

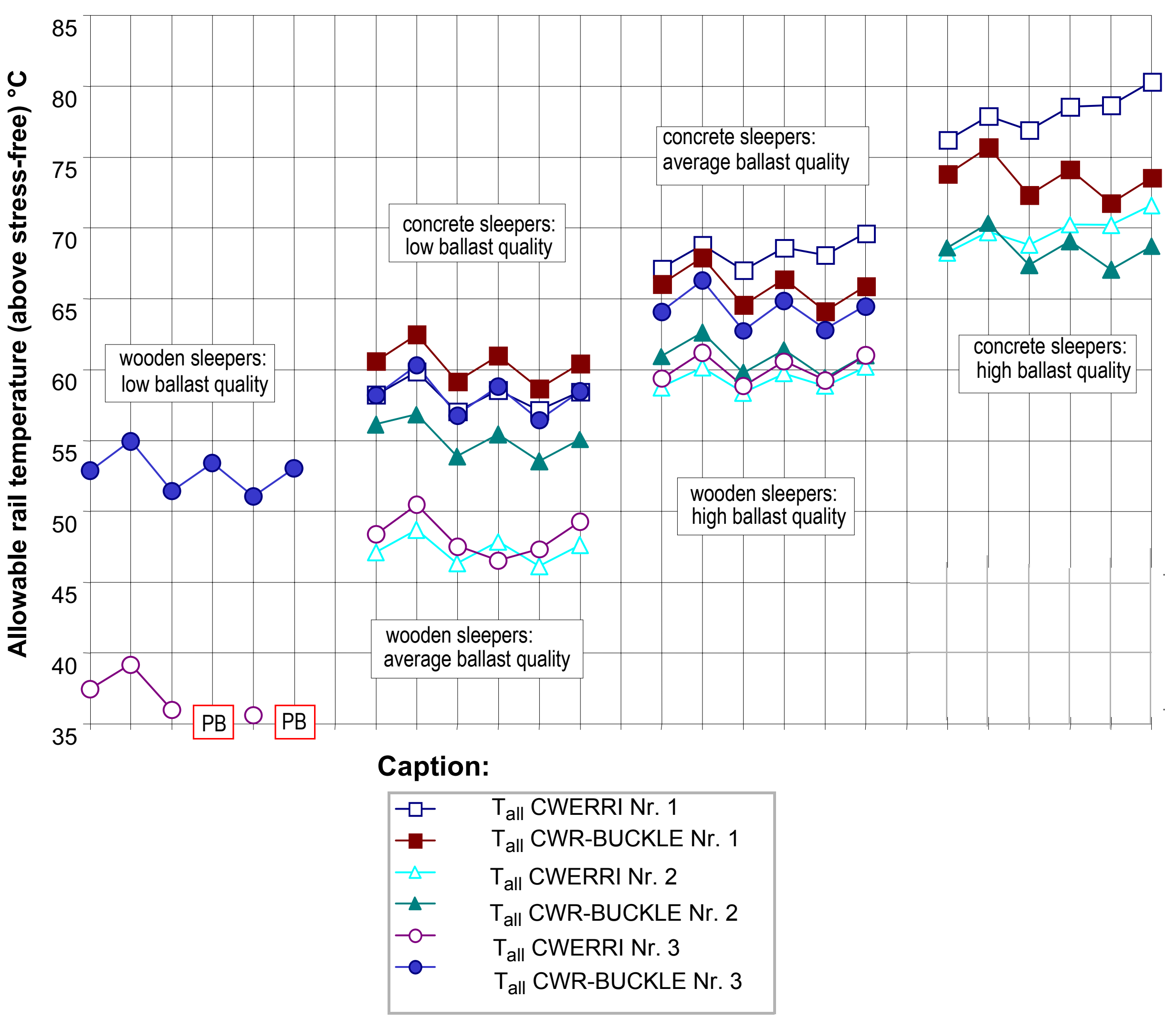
In this example $T_{b,max}$ and $T_{b,min}$ values are calculated and displayed below.

For track safety calculations (which are in fact more precise estimations), the following concept of safety should be maintained as stated in Appendix A - page 20.

For all **CWERRI** calculations, first ΔT is calculated by $(T_{b,max} - T_{b,min})$.

If $\Delta T > 20°C$:	$T_{all} = T_{b,min} + 25\%$ of ΔT
If $5°C < \Delta T < 20°C$:	$T_{all} = T_{b,min}$
If $0°C < \Delta T < 5°C$:	$T_{all} = T_{b,min} - 5°C$
If $\Delta T < 0°C$:	not allowable on main lines

Overview of safety temperatures T_{all} of track structures Nr. 1, 2 and 3



NB: For each ballast quality, two alternatives are shown with increasing torsional stiffness and three alternatives with increasing misalignment length and amplitude.

Fig. 9 - CWERRI and CWR-BUCKLE results for safety temperatures for high-speed and main-line tracks

In the last case progressive buckling (PB) occurs, which means that elastic and plastic lateral deformation easily fade into each other (Figure 7 - page 35). PB is strongly related to low ballast quality track structures.

For all **CWR-BUCKLE** calculations, the following criteria are always maintained:

$$T_{all} = T\{0,5\ E_{max}\} = 50\%\ BET$$

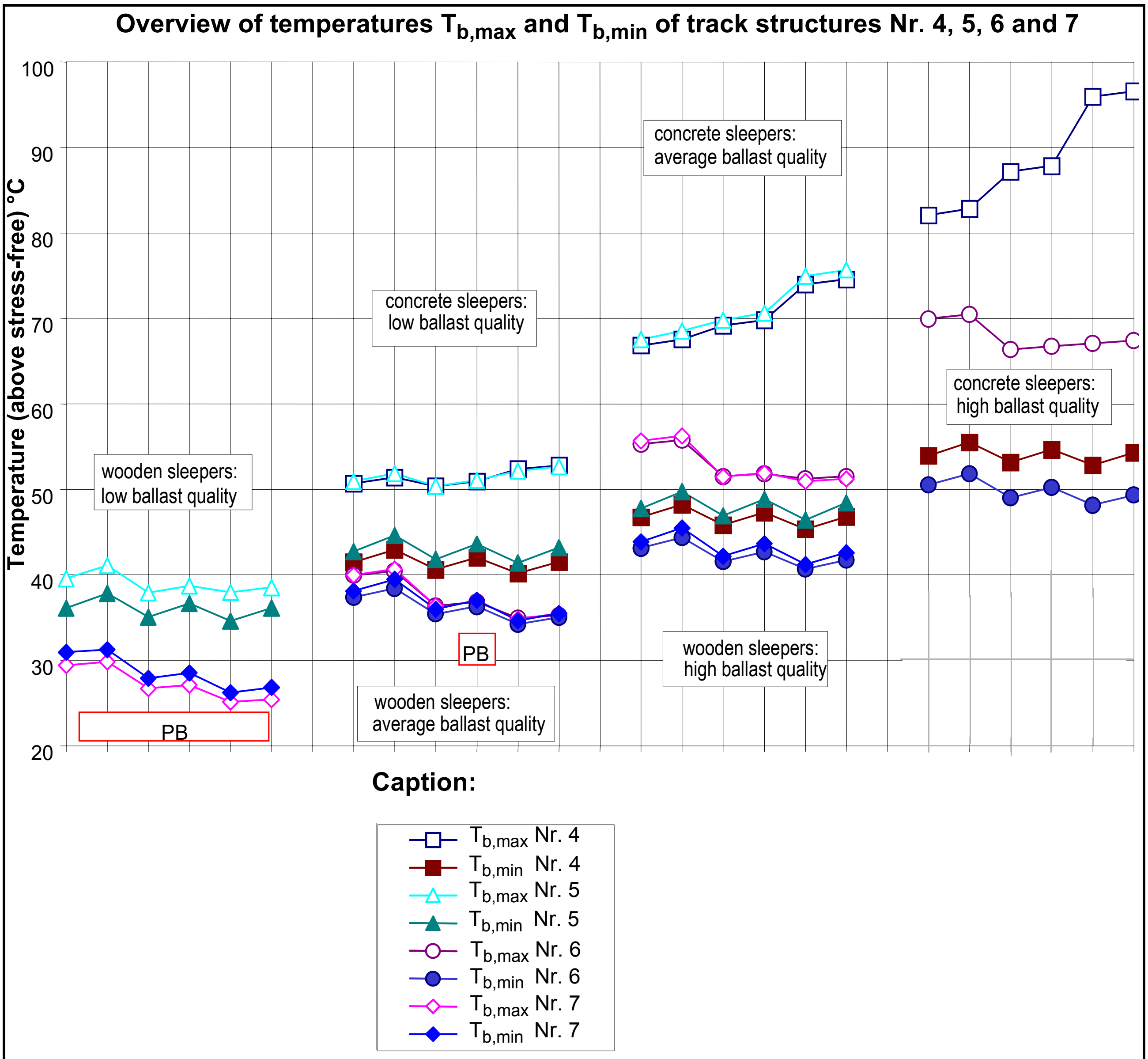
B.3 - Example 2: Secondary and freight-line tracks

An EC1 freight vehicle was used for the calculations for these two track structures. Compared to other vehicles or coaches, this vehicle causes minimum total rail deflection between inner axles, which makes the track structure highly susceptible to lateral buckling. Calculations have been performed with UIC 60 rails and a vertical track stiffness of 70 MN/m/m'.

Different track properties are represented:

Structure type and number	Curve radius (mm)	Sleepers (tan φ)	Lateral ballast resistance (kN/m')	Torsional resistance of fastening (kNm/rad/m')	Misalignment (mm)
Secondary-line track (4)	600	Concrete friction 0,86	10/10, 15/12, 20/16	75, 150	14/18/22
Secondary-line track (5)	600	Wooden friction 1,2	7/7, 10/10, 15/12	150, 250	14/18/22
Freight-line track (6)	300	Corrective friction 0,86	10/10, 15/12, 20/16	75, 150	14/22/30
Freight-line track (7)	300	Wooden friction 1,2	7/7, 10/10, 15/12	150, 250	14/22/30

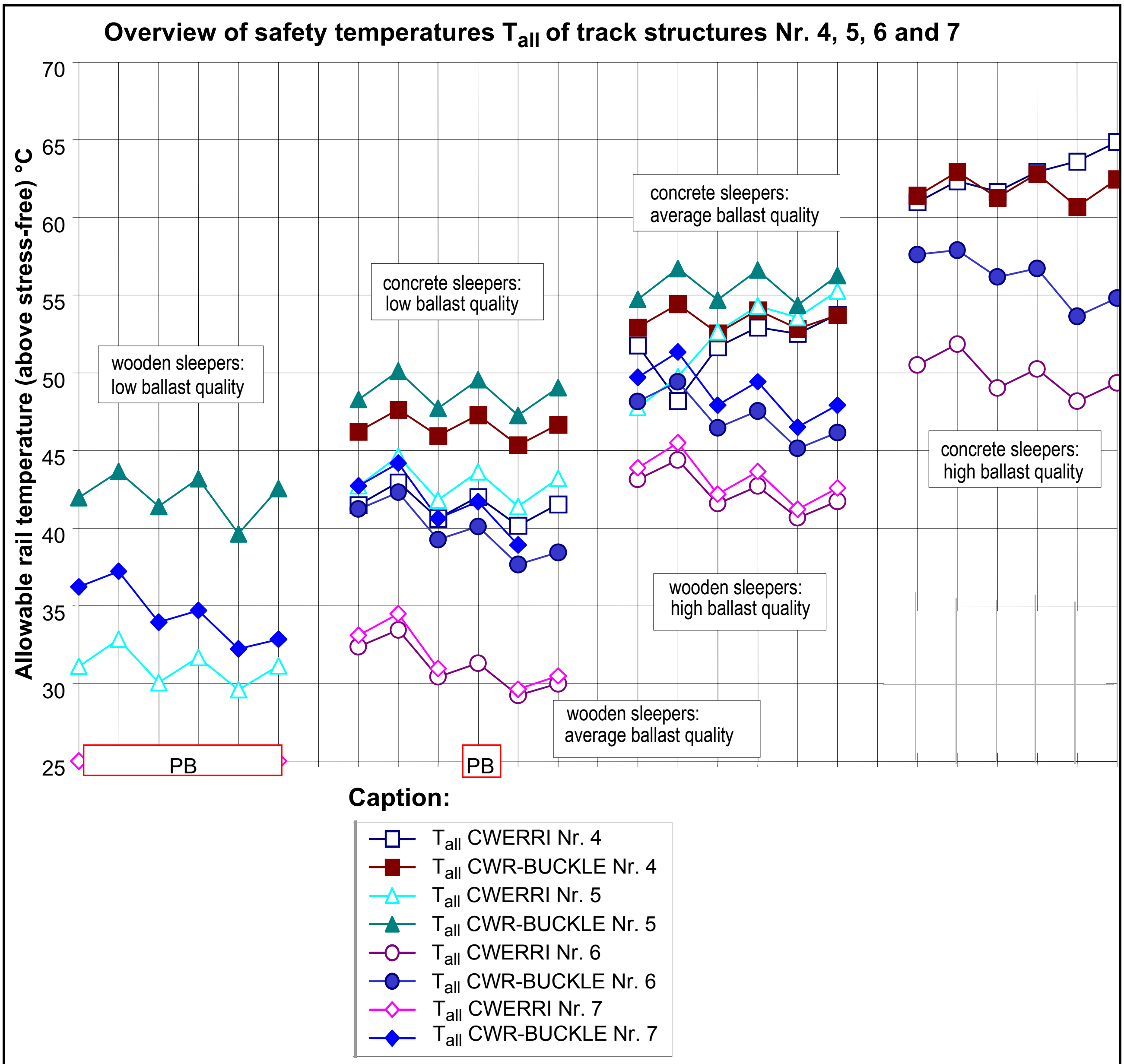
For remarks concerning this Table, the reader is referred to the remarks in the Table of Example 1 - page 36 of this point. The same is noted for track safety concepts and calculation criteria. In the present example, $T_{b,max}$ and $T_{b,min}$ values are calculated and displayed below:



NB: For each ballast quality, two alternatives are shown with increasing torsional stiffness and three alternatives with increasing misalignment length and amplitude.

Fig. 10 - CWERRI temperature results for secondary-line and freight-line tracks

Finally, the T_{all} values are depicted below also:



NB: For each ballast quality, two alternatives are shown with increasing torsional stiffness and three alternatives with increasing misalignment length and amplitude.

Fig. 11 - CWERRI and CWR-BUCKLE results for safety temperatures for secondary-line and freight-line tracks

B.4 - Application of results

For track safety, T_{all} is the maximum allowable temperature above the stress-free temperature of the rail that is **considered safe** as far as track buckling is concerned. T_{all} can be seen as a buffer with regard to many phenomena that increase rail temperature or an equivalent axial compressive stress in the rail, pushing it into the dangerous "buckling" range. These phenomena are:

- air temperature,
- sunlight,
- eddy-current brakes,
- interaction with other structures, such as bridges.

The first and second items generally take up about 30-40°C of the available temperature buffer, depending on local circumstances. This means that specific structures with a T_{all} value lower than 40°C will certainly encounter buckling problems in summer or under high temperature conditions. With T_{all} above 40°C, track structures can be exposed to eddy-current brakes or to external forces from other structures, as long as the equivalent temperature increase remains within the calculated temperature buffer.

B.5 - General remarks

Figure 9 - page 38 and Figure 10 - page 40 show the results of the calculations for several different track structures, calculated with two different programs and with two different criteria for the safety temperature. It is noticeable that the differences in the results for similar track structures with small, moderate and large misalignments are quite small (< 5°C), while the differences for low, average and high ballast quality are almost constant (8.5-10°C for CWERRI results, 6-9°C for CWR-BUCKLE results). These differences between two ballast qualities are larger than the differences between $T_{b,min}$ values for two ballast qualities. It can be concluded that the values of $T_{b,max}$ (CWERRI) and energy absorption (CWR-BUCKLE) for specific track structures increase more than linearly if ballast quality and $T_{b,min}$ increase. The differences in the results for concrete-sleeper and wooden-sleeper track structures are almost negligible for equal ballast qualities.

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