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Translation

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Design requirements for rail-bridges based on interaction phenomena between train, track and bridge

Exigences dans la conception des ponts-rails liées aux phénomènes dynamiques d'interaction véhicule-voie-pont

Anforderungen für die Planung der Eisenbahnbrücken in Bezug auf die dynamischen Wechselwirkungen Fahrzeug - Gleis - Brücke



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Summary

The procedures for verifying the strength of railway bridges are covered by detailed and comprehensive rules of calculation already in existence. In contrast, serviceability limit states, notably deformation ELS, are described only in network calculation rules or in UIC leaflets.

In essence, bridges are deformable structures. These deformations must be controlled all the more accurately as trains travel at high, and very high speeds. The purpose of this leaflet is to specify the design requirements for rail-bridges as regards train/track/bridge interaction phenomena and in particular speed, thereby taking into account bridge resonance phenomena. It outlines the corresponding draft criteria and provides information on the phenomena to be controlled as well as the appropriate procedures for verifying the structures.

This leaflet should be used in conjunction with *UIC Leaflet 776-1*.

1 - Introduction

1.1 - Role of rail-bridges

Rail bridges are designed to guarantee continuity of the rail platform so as to ensure the movement of traffic in the same conditions of safety and comfort as on normal tracks and at any traffic speed up to the crossing speed limit defined for this bridge and for all types of traffic scheduled to cross the structure.

1.2 - Purpose of this leaflet

The procedures for verifying the strength of railway bridges are covered by detailed and comprehensive rules of calculation already in existence. In contrast, serviceability limit states, notably deformation ELS, are described only in network calculation rules or in UIC leaflets.

In essence, bridges are deformable structures. These deformations must be controlled all the more accurately as trains travel at high, and very high speeds. The purpose of this leaflet is to specify the design requirements for rail-bridges as regards train/track/bridge interaction phenomena and in particular speed, thereby taking into account bridge resonance phenomena. It outlines the corresponding draft criteria and provides information on the phenomena to be controlled as well as the appropriate procedures for verifying the structures.

This leaflet should be used in conjunction with *UIC Leaflet 776-1* (see Bibliography - page 43).

1.3 - Train-track-bridge interaction

In order to properly assess these phenomena, it is best to examine the effects of both primary and secondary suspensions of the vehicles as well as the associated masses, the behavioural effects of the track and the deformability of the bridge deck and its supports.

This leaflet also contains more simple alternative methods giving acceptable results using common calculations.

Aside from its vertical component which is the most critical and which constitutes the greater part of this leaflet, train-track-bridge interaction also has a lateral component that has a bearing on lateral vehicle behaviour through the effects of the suspension, while also exercising an influence, albeit to a lesser degree, on the track and on the bridge.

1.4 - European Regulations

These phenomena have been studied in far greater detail as part of the preparatory work into "Eurocodes" European regulations which now make bridge dimensioning possible by looking at the effects of train-track-bridge interaction, irrespective of the proposed speed of traffic up to 350 km/h and irrespective of the type of trains to be operated.

2 - Definitions

2.1 - List of symbols

E	=	Young's modulus of the material [kN/mm ²]
E_c	=	Static modulus [kN/mm ²]
E_{cq}	=	Dynamic modulus [kN/mm ²]
E_{cm}	=	Secant modulus of elasticity
G	=	Shear modulus [kN/mm ²]
I	=	Moment of inertia of the deck cross section
I_c	=	Intermediate cracking or 'partially cracked' state of inertia
I_G	=	Gross moment of inertia of the uncracked transformed section
I_{CR}	=	Moment of inertia of the fully cracked transformed section
L_c	=	Characteristic distance (e.g. span length or vehicle length)
L	=	Length of the deck
M_{cr}	=	Serviceability limit state cracking moment
M_A	=	Maximum moment due to service loads at serviceability limit state
P	=	Maximum axle load of the load train (articulated train)
P'	=	Maximum axle load of the load train (conventional train)
V_{crit}	=	Critical speed in relation to the resonance phenomenon
V_{lim}	=	Speed limit giving the upper limit where no dynamic calculations are necessary
V	=	Actual train speed (in general) [km/h]
V_{pro}	=	Speed of project
V_{ligne}	=	Maximum line speed
Φ_2	=	Dynamic increment coefficient for rail bridges (tracks with superior maintenance)
Φ_3	=	Dynamic increment coefficient for rail bridges (tracks with standard maintenance)
Φ	=	Dynamic increment coefficient
a	=	Acceleration of the deck
a_{max}	=	Maximum acceleration of the deck
b	=	Length of longitudinal distribution of a load across a sleeper and ballast
b_v	=	Vertical acceleration in the vehicle

d	=	Axle spacing of the bogies of the load train
D	=	Bogie spacing of the load train
f_{ck}	=	Characteristic compressive strength of the concrete [kN/mm ²]
m	=	Mass of deck per unit length
η_j	=	Natural bending frequency of row j of the unloaded deck [Hz]
n_0	=	First natural bending frequency of the unloaded deck [Hz]
n_T	=	Natural torsion frequency
t	=	Distortion of the deck
δ_0	=	Deflection calculated at mid-span of the deck due to permanent loads (own weight + superstructure) applied in the direction of the deflection
α	=	Classification coefficient
δ_{dyn}	=	Deflection at mid-span under dynamic operating loads
δ_{stat}	=	Deflection at mid-span under static operating loads
δ_H	=	End displacement of the supports under operating loads
φ	=	Dynamic increment component for real trains
φ'	=	Dynamic increment for the real train and for a track without irregularities
φ''	=	Dynamic increment for the real train taking into account track irregularities
θ_{stat}	=	Rotation of the end of the deck under the influence of static operating loads
θ_{dyn}	=	Rotation of the end of the deck under the influence of dynamic operating loads
ζ	=	Damping coefficient or % of critical damping
ν	=	Poisson's coefficient

2.2 - Bridge deformations and displacements

Bridge deformations and displacements occur under the effect of external action applied through the spanned rail tracks, the deck supports or even directly onto the deck. These deformations and displacements are described below.

2.2.1 - Static deformations

The vertical operating loads applied to the bridge cause the deck to bend, resulting in a vertical displacement of every point on the surface of the deck. In general, maximum displacement occurs at the point in the middle of the deck, or at mid-span. This displacement is known as the deflection of the deck. When the loads are static, the deflection reading δ_{stat} is called the static deflection.

The vertical deflection of the deck considered for each span (isostatic or continuous bridge or succession of decks) is important in determining the final vertical radii of the track.

The deflection of the deck described above causes rotation of the ends of the deck. Fig. 1 shows the rotation of each deck along a transversal axis or the total relative rotation between the adjacent ends of the deck. Static operating loads are used to define a rotation of θ_{stat} .

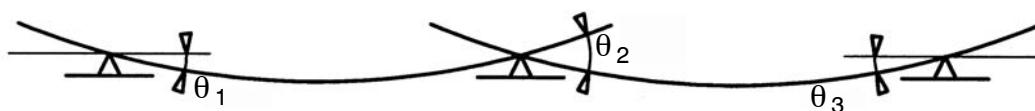


Fig. 1 - Definition of angular rotation of the ends of the decks

The deck demonstrates transversal horizontal static deflection in response to certain actions. This is important in determining the final horizontal radii of the track.

Because of the horizontal deflection of the deck (or the succession of decks) it is possible to observe a horizontal rotation of the decks around a vertical axis at their ends. This has a bearing on the horizontal geometry of the track.

Whenever the deck supports a non-centred track or several tracks, of which one is loaded, it undergoes torsion as a result of the operating loads. Distortion of the deck is measured along the axis of each track in proximity to a bridge or on the bridge.

Distortion t_{stat} under static operating loads is measured on a track 1 435 mm wide and over a distance of 3 m (cf. Fig. 2).

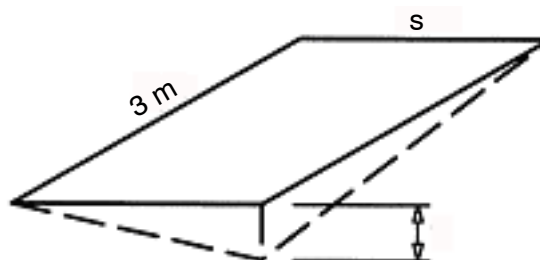


Fig. 2 - Definition of deck distortion

As shown in Fig. 3 - page 6, deflection of the deck under operating loads causes the end of the deck behind the support structures to lift. There is also a longitudinal displacement of the ends of the upper surface of the deck as a result of rotation of the end of the deck.

The deformability of the bridge support structures causes longitudinal horizontal displacements of the bridge. Displacement covers the entire bridge in case of a single deck but it is relative in case of a series of decks.

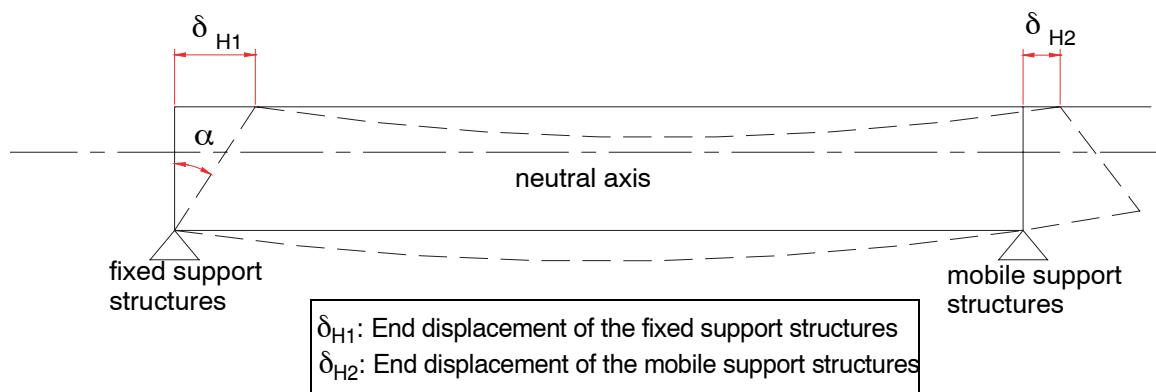


Fig. 3 - Definition of end displacements of a deck

2.2.2 - Dynamic deformations

All the deformations and displacements described earlier as taking place under static loads show different values under dynamic loads (in general, all the more higher if train crossing speeds are greater), whether they are vertical or horizontal deflections under operating loads, vertical and horizontal end rotations, or longitudinal end displacements as well as lifting of the ends of the deck.

Under dynamic loads, these deformations are expressed as follows: δ_{dyn} , δ_{Hdyn} , θ_{dyn} .

Distortion also takes on a different value under the dynamic effect of operating loads. This is expressed as follows: dynamic distortion t_{dyn} .

In general, the value retained is the maximum value obtained for a given speed.

3 - Requirements for train traffic safety

3.1 - Phenomena

3.1.1 - Quality of the wheel-rail contact

Excessive deformation of the bridge can jeopardise train traffic safety by causing unacceptable changes in the vertical and horizontal geometry of the track, excessive rail stress and excessive vibrations in the bridge support structures. In the case of ballasted bridges, excessive vibrations could destabilise the ballast. Excessive deformation may also affect the loads imposed on the train/track/bridge system, as well as create conditions that lead to passenger discomfort.

3.1.2 - Track stability

Relative displacements of the track and of the bridge, caused by a possible combination of the effects of train braking/starting, deflection of the deck under operational loads, as well as thermal variations, lead to the track/bridge phenomenon that results in additional stresses to the bridge and the track.

It is important to ensure track stability as this may be compromised by additional stresses in the rail during compression (risk of buckling of the track, especially at bridge ends) or traction (risk of rail breakage). It is also important to minimise the forces lifting the rail fastening systems (vertical displacement at deck ends), as well as horizontal displacements (under braking/starting) which could weaken the ballast and destabilise the track. It is also essential to limit angular discontinuity at expansion joints and at points and switches in order to reduce any risk of derailment.

3.2 - Criteria

3.2.1 - Distortion

Distortion of the deck is calculated with the characteristic value of load model UIC 71 and with load diagrams SW/0 or SW/2 as necessary multiplied by Φ and α or the high-speed load diagram, including the effects of centrifugal force. Limit values of distortion as described before are described in Table 1.

Table 1 : Limit values of deck distortion

Speed domain V (km/h)	Maximum distortion t (mm/3m)
$V \leq 120$	$t \leq 4,5$
$120 < V \leq 200$	$t \leq 3,0$
$V > 200$	$t \leq 1,5$

Total distortion caused by distortion of the track when the bridge is not loaded (for example in a transition curve), and distortion due to total deformation of the bridge, must not exceed 7,5 mm/3m.

3.2.2 - Horizontal and vertical displacements

If continuous tracks are used, longitudinal horizontal displacements under the vertical effects of operating loads must remain below 10 mm.

If continuous tracks are used, longitudinal horizontal displacements under the effects of braking/starting must remain below 5 mm. They should be limited to 30 mm if the track has continuous welded rails and is fitted with an expansion joint at the end of the bridge, or if the track is fitted with scarfed joints.

Vertical displacements at the ends of the deck should remain below 3 mm if the track is ballasted and 1,5 mm if the track is laid directly.

3.2.3 - Acceleration of the deck

The risk of excessive vibrations of the deck corresponds to its levels of acceleration and consequently of the spanned track, and this should be verified. Deck acceleration should be considered a serviceability limit state as far as operating safety is concerned. In cases where the bridges have ballasted tracks, intense accelerations of the deck create the risk of destabilising the ballast. For this reason, it is important to ensure that maximum acceleration of the deck remains below 0,35g for frequencies up to 30 Hz.

When verifying the acceleration of a deck with dual tracks in both running directions, it is assumed that only one track is loaded.

In the case of bridges with slab tracks, the acceleration limit value is set at 0,5g for frequencies below 30 Hz.

Dynamic analysis using the modal superposition method should take on board at least 3 modes as well as frequency vibration modes up to 1.5 times the frequency of the first mode.

4 - Requirements for structural strength

4.1 - Phenomena

4.1.1 - Strength

This involves checking the ability of a structure, an element or a structural component, or a transverse section of an element or structural component to withstand actions without mechanical deterioration, for example bending strength and tensile strength also under dynamic effects.

The strength calculation value of the structure or its elements must be greater than the calculation value of the corresponding action effects.

4.1.2 - Fatigue

Fatigue describes the progressive damage to structures subjected to fluctuating or repeated stress, caused by the development of cracks that may eventually lead to their destruction.

Fatigue increases with the number and the weight of trains, as well as with their speed.

Fatigue service life should be sufficient to avoid any risk of cracking during the expected service life of the structure (usually, a minimum of 100 years).

4.1.3 - Durability

The structure must be designed in such a way that its deterioration, during the period of use of the construction, does not jeopardise its durability or performance within its environment and in relation to the projected level of maintenance. Adequate measures are specified in order to limit deterioration on the basis of certain factors (such as properties of the soil, of the materials, foreseen maintenance during the life cycle of the structure, etc...).

4.2 - Criteria

4.2.1 - Dynamic increment coefficient

When a dynamic analysis of the structure needs to be carried out (see Appendix A - page 16), with the relevant load models or real trains, it is important to determine the following dynamic increment coefficient:

$$\varphi'_{\text{dyn}} = \max [\gamma_{\text{dyn}} / \gamma_{\text{stat}}] - 1$$

where γ_{dyn} represents the dynamic deflection of the deck under the high-speed load diagram or real trains and γ_{stat} represents the static deflection of the deck.

The bridge is assessed using the logic diagram shown in Fig. 4.

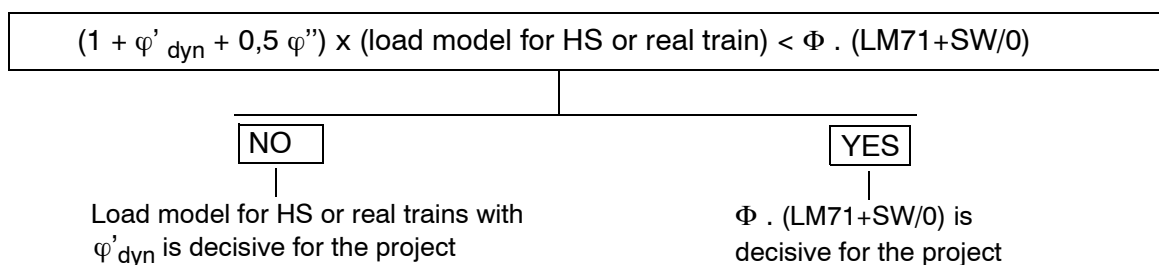


Fig. 4 - Logic diagram determining the loads to be taken into account for calculating bridge strength

4.2.2 - ELU constraints

The resistance criterion involves checking that the calculation constraint of the effect of the actions is lower than or equal to the corresponding resistance constraint and remains so within the framework of the verification of the resistance limit-status.

4.2.3 - ELS constraints

The non-cracking and reversibility criteria, part of the ELS verifications, involve checking the material stresses to ensure that the materials do not present a risk of developing irreversible deformations. The limit values with regard to constraints are given in the Eurocodes.

They also involve for stressed concrete structures checking the limitation of crack openings. Such verifications may require making minimal reinforcements in the concrete.

4.2.4 - Fatigue damage

Fatigue damage is a quantitative notion defined by a value between 0 and 1, and used to assess the relative evolution of cracking. The value is 0 if there is no damage and 1 if propagation is such that it destroys the structural element. Damage is determined by taking into account the successive loading of the component, which must remain at a permissible level for the lifetime of the structure. Fatigue dimensioning must be done to allow for the most unfavourable fatigue load conditions.

5 - Requirements for passenger comfort

5.1 - Physical phenomena

5.1.1 - Train-track interaction

Track levelling and lining variations generate vehicle movement that can affect passenger comfort and train safety. Almost every vehicle is mounted onto bogies.

The movements that have a bearing on the vehicles are due to track levelling and lining defects (or track irregularities), the natural hunting movements of the axles and, when crossing bridges, the deformation of the bridge which modifies the path of the bogies.

The running gear and suspensions generate rail vehicle body movement which affects passenger comfort and stresses which influence the vehicle running safety.

The vehicle integrates primary and secondary suspensions (springs and dampers) as well as sprung and unsprung masses (masses, rotating masses inertia) that have an impact on this phenomenon. In order to separate the movements of the bogie from those of the body, the greatest possible vertical and transversal flexibility is required for secondary suspension. The required natural suspension frequencies are about 0,7 Hz (at present, 1 Hz is usually obtained but this can vary between 1 and 2 Hz).

5.1.2 - Passenger comfort in vehicles when crossing bridges

In order to establish a maximum value that effectively translates the accelerations within the vehicle, it is important to know how vibrations impact passenger well-being. A certain number of physiological criteria linked to frequency, intensity of acceleration, steering relative to the spinal column and time of exposure (duration of vibrations) make it possible to assess vibrations and their influence on individuals. The limit exposure time to reduced comfort represents the limit of comfort adopted. This paragraph characterises the flexibility of bridges with regard to comfort.

With knowledge of the dynamic deflection under a real train at mid-span on a civil engineering structure, it is possible to give an approximation of the path of a bogie during its passage over the structure. Knowing the transfer function that makes it possible to move from the path of the bogie to that of the body, it is possible to calculate vehicle acceleration. The acceleration limits inside the vehicles depend on the desired level of comfort and make it possible to limit the deflection of the structure.

5.1.3 - Physiological fatigue of passengers

The preceding notion of comfort must nevertheless be reviewed whenever structures are very long, making for lengthy crossing times.