



**HAL**  
open science

# Effects of the diaphragm at midspan on static and dynamic behaviour of composite railway bridge: A case study

Yannick Sieffert, Gérard Michel, Philippe Ramondenc, Jean-Francois Jullien

## ► To cite this version:

Yannick Sieffert, Gérard Michel, Philippe Ramondenc, Jean-Francois Jullien. Effects of the diaphragm at midspan on static and dynamic behaviour of composite railway bridge: A case study. *Engineering Structures*, 2006, 28 (11), pp.1543-1554. 10.1016/j.engstruct.2006.02.011 . hal-02004132

**HAL Id: hal-02004132**

**<https://hal.science/hal-02004132v1>**

Submitted on 11 Jan 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Effects of the diaphragm at midspan on static and dynamic behaviour of composite railway bridge: A case study

Yannick Sieffert<sup>a,\*</sup>, Gérard Michel<sup>b</sup>, Philippe Ramondenc<sup>c</sup>, Jean-François Jullien<sup>b</sup>

<sup>a</sup> *Laboratory Sols, Solides, Structures (formerly at URGC INSA), Domaine universitaire, B.P. no. 53, 38041 Grenoble Cedex 9, France*

<sup>b</sup> *URGC, INSA, 20 Avenue Albert Einstein, 69621 Villeurbanne Cedex, France*

<sup>c</sup> *SNCF, Direction des Ouvrages d'Art, 6 Avenue François Mitterrand, 93210 La Plaine Saint-Denis, France*

Received 17 May 2004; received in revised form 7 February 2006; accepted 8 February 2006

Available online 17 April 2006

## Abstract

This study focuses on composite multi-girder railway bridges of moderate span for high-speed trains. In this type of bridge the concrete deck is the primary element of transverse rigidity, so the real impact of cross beams is unknown. These cross beams increase the cost of this type of bridge, because they require handling and welding on site. This research studies the impact of a diaphragm in a typical multi-girder railway bridge used in France. The first objective is to develop appropriate modelling techniques that can be used to evaluate the function and effectiveness of a diaphragm in the transverse distribution of traffic loads. The second objective is to know if a diaphragm is really necessary. To answer this question, a three-dimensional model and nonlinear material constitutive equations are considered. Different static loading conditions (self-weight, UIC load, and TGV) are studied and the bridge deck responses to them with and without transverse diaphragm are analyzed. The TGV is modelled with moving loads in order to take into account the dynamic behaviour of the bridge deck. Several critical speeds of train corresponding to natural frequencies are then studied in dynamic analysis. Our static and dynamic analyses concluded that the diaphragm does not seem to be necessary, except for an accidental lateral load. Therefore, it may be possible to not install diaphragms on these bridges.

© 2006 Elsevier Ltd. All rights reserved.

*Keywords:* Concrete; Steel; Bridge; Composite; Multi-girder; Diaphragm; Speed train

## 1. Introduction

Multi-girder steel bridges are common throughout the world. In France, composite multi-girder bridges are frequently used for road traffic, but also for railway traffic. The girder span follows the direction of traffic and is used as a primary load bearing the structure. The concrete reinforced slab is connected to the girders, thus it increases the rigidity of the girders and provides a plane surface for live traffic. The thickness of the slab and the height of the girders for railway bridges can be twice as high as for road bridges. Indeed, the stability of the rail/wheel contact requires very significant rigidity in the structure and very small deflection under the traffic track. Transverse steel components or diaphragms are used to connect the slab and

the girders in order to transmit the loading of the slab to every girder. The diaphragm is an essential element of stability for twin-girders, enabling the slab in the transverse direction to be rigidified and the stresses on each girder to be transmitted. In the case of a multi-girder, the concrete slab is supported by a greater number of longitudinal girders. The distance between the girders is reduced, so the transverse bending of the slab is limited. The necessity of an intermediate diaphragm then becomes less relevant.

A review of the available literature clearly indicates that the contribution of the diaphragm is not really known: the recommendations of the various authors are contradictory. For example, Stevens and Gosbell [1] conclude that intermediate diaphragms do not significantly affect live load distribution. On the other hand, Culham and Ghali [2] find that intermediate diaphragms do affect the transverse distribution of the live load. This contradiction can be explained by the fact that each study was carried out on an arbitrarily chosen bridge. The difference in the manner of modelling the behaviour of the bridges could

\* Corresponding author. Tel.: +33 476827014; fax: +33 476827043.

E-mail addresses: [Yannick.Sieffert@ujf-grenoble.fr](mailto:Yannick.Sieffert@ujf-grenoble.fr) (Y. Sieffert), [Gerard.Michel@insa-lyon.fr](mailto:Gerard.Michel@insa-lyon.fr) (G. Michel), [Phillipe.Ramondenc@snec.fr](mailto:Phillipe.Ramondenc@snec.fr) (P. Ramondenc), [Jean-Francois.Jullien@insa-lyon.fr](mailto:Jean-Francois.Jullien@insa-lyon.fr) (J.-F. Jullien).

also be another explanation. This study aims first to develop appropriate modelling techniques that can be used to evaluate the function and effectiveness of diaphragms in the transverse distribution of traffic loads.

The major problem of diaphragms on multi-girders is the realization of the welds between the diaphragm and the girders; the cost of welds is not negligible compared to the cost of the structure. Moreover, cracking due to fatigue is often observed in girder webs and diaphragm/girder connections such as those discussed by Fisher and Keating [3]. When damage at the diaphragm/girder connection is noticed, the most potentially successful solution to repair this is to remove the diaphragms [4]. Successful repair by removal leads us to think that a bridge without a diaphragm is possible and more effective. Then these multi-girder composite bridges would be more cost effective in comparison to a concrete bridge. The second objective is to conclude whether the diaphragm is unnecessary.

However, it seems difficult, in some cases, to remove the diaphragm, as it provides better resistance in case of an accidental lateral loading and also stabilizes the girders during construction and placement of the deck.

## 2. Model development to evaluate the function of the diaphragm

### 2.1. Bridge mesh

The behaviour of multi-girder bridges was studied extensively between the 1960s and 1980s. At that time, the behaviour of bridges was modelled as a planar grillage beam system. However, to understand the diaphragm contribution in transverse loading, Chen in 1993 [5] modelled I-shape girders and diaphragms with beam elements and the slab with shell elements. The composite action between slab and girder is modelled by connecting the centre of gravity of the slab and of the girder with rigid link elements. Tedesco et al. in 1995 [4] used shell elements for flanges, webs, and for the slab. They did not use shell elements for diaphragms but beam elements with rigid links, as their mesh did not enable them to correctly associate the position of the diaphragm with the mesh representation of web girders. This requires a very fine mesh with a great number of elements in order to enable a detailed representation of the different structural elements.

So as not to weigh down the models, only the significant zones are usually meshed more finely (such as assembly zones and zones of high constraints). The remainder of the structure — not being the place of significant phenomenon development — is meshed more coarsely. But, in the case of a bridge, this method is not possible, due to the moving load moving on the bridge. To ensure the pertinence of the results, the size of the elements must be the same on the whole surface of the load's displacement. This fine mesh is necessary for a dynamic analysis, but not for a static loading, as the load does not move. However, in order not to create the influence of the mesh on the results, this fine mesh has been kept for all the analyses.

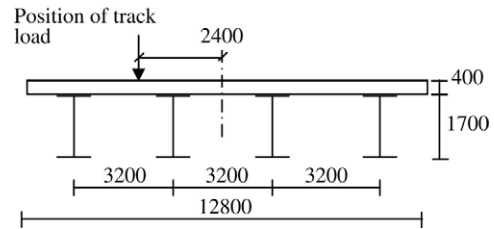


Fig. 1. Cross-section of the bridge system.

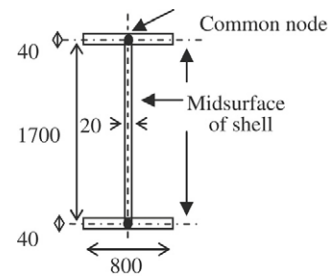


Fig. 2. Girder detail.

### 2.2. FEM model

The finite element modelling (FEM) analyses were conducted on a Unix station through implementation of the ABAQUS version 6.3 [7] finite element computer programs.

In order to investigate the contribution of the intermediate diaphragm in composite multi-girder bridges, we chose to model an existing bridge owned by the French National Railway Company (SNCF). This bridge is situated at BONPAS, on the new high-speed line connecting Lyon to Marseille. This bridge was selected for this study for its simplicity. It has a simply-supported span of 30 m with no skew and carries two tracks. It has four 1.7 m high steel girders spaced transversely at 3.2 m, and a 0.4 m thick reinforced concrete deck slab (Figs. 1 and 2). Its simplicity enables us to regard it as a general composite four-girder bridge.

The flanges of the girders are essentially in a state of plane stress. Therefore, the flanges were modelled with the four node shell elements with five degrees of freedom (DOF) per node (S4). The same elements are used to model the webs, to take into account their out-of-plane bending. To obtain an identical stiffness between the girder flanges and those of the diaphragms, four elements are used in the width of the flanges, girders and diaphragms (Fig. 3).

In order to model the concrete slab, Tedesco et al. [4] also used shell elements for the slab, because its thickness is not very important. In the case of a high-speed train bridge, the thickness of the slab deck is more important and requires an approach with a volume element in order to consider the stress in the thickness (Fig. 4). The element of volume enables us to assess the distribution of the stresses and the cracks occurring in the slab [8]. We used eight-node volume elements (C3D8). Moreover, to describe the behaviour of the concrete slab correctly, we modelled the reinforcements with two-node bar elements (B31) in the first and last layers of volume elements.

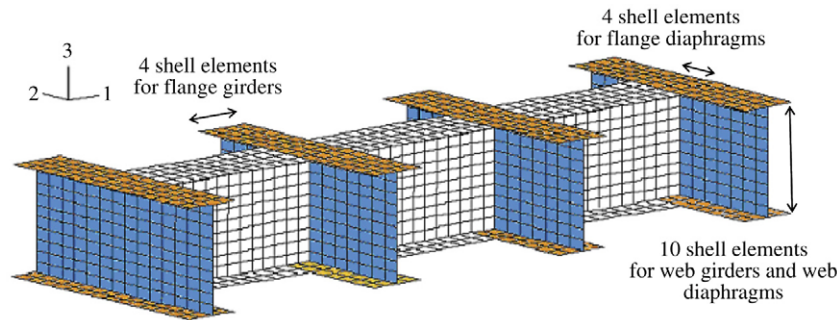


Fig. 3. Diaphragm-to-girder connection detail.

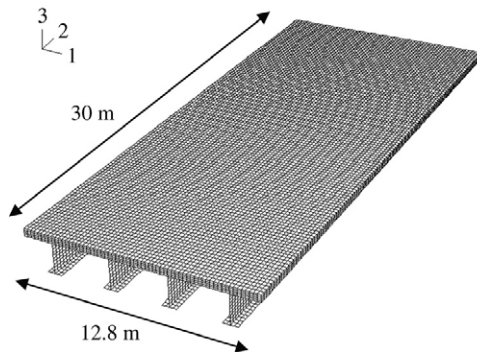


Fig. 4. Isometric view of FEM model.

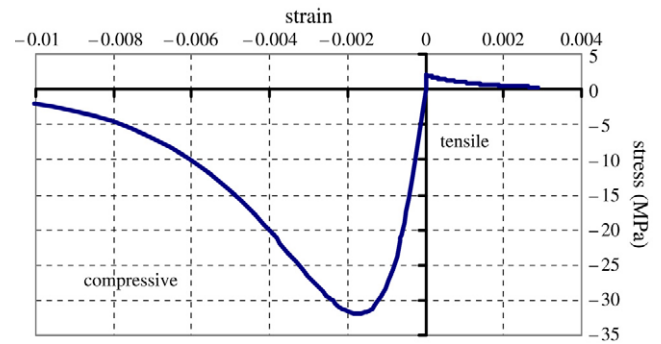


Fig. 5. Concrete model for uniaxial stress–strain law.

2.3. Materials model — non-linear constitutive equation

Today, the modelling of concrete behaviour is still a significant numerical problem, due to its very strong non-linearity and the presence of negative hardening in tension. Historically, some composite multi-girder bridge studies consider the concrete as perfectly elastic [1,9]. More recently, the concrete slab in composite multi-girders has been regarded as always compressed with a constitutive plasticity equation [6, 10], or the cracking of the slab is taken into account before the analysis thanks to an orthotropic description of the concrete [4]. Without the diaphragm, the transverse bending of the deck is significant and the concrete slab between two consecutive beams is then subjected to tensile stresses. It is thus important to use concrete damaged plasticity material models which assume that the main two failure mechanisms are tensile cracking and compressive crushing. Zhou et al. in 2004 [8] used a non-linear constitutive equation for the concrete slab in a similar bridge with ANSYS 5.7 software [11]: it was observed that, at high levels, the overall solution does not converge.

The concrete damaged plasticity model developed by Lubliner et al. [12] and completed by Lee and Fenves [13] is implemented in ABAQUS version 6.3. It supposes that the two main mechanisms of failure are tensile cracking and compressive crushing of the concrete material. The evolution of the yield surface is controlled by two hardening variables,  $\tilde{\epsilon}_t^{pl}$  and  $\tilde{\epsilon}_c^{pl}$ , linked respectively to failure mechanism under tension and compression loading. The material model is based on a uniaxial stress–strain relation (Fig. 5) that is generalized to take biaxial and triaxial stress conditions into account.

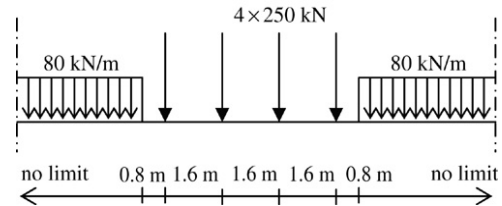


Fig. 6. UIC loading.

The behaviour of steel is regarded as perfectly plastic, with a limit of elasticity of 355 MPa.

With ABAQUS software, we had the same difficulty when we used a concentrated load for a wheel model. On the one hand, this concentrated load leads to a localization of the stresses and results in no convergence. On the other hand, it is not representative of the real loading or of the effect of ballast distribution, as discussed in the following section.

2.4. High-speed trains (TGV)

The bridge of BONPAS carries two tracks. The loads are not in the centre of the bridge, but are situated 2.4 m from the bridge centre (Fig. 1). Eurocode 1 [14] defines a train load called UIC 71, which is eight times higher than TGV loads, for rail bridge dimensioning (Fig. 6). This loading leads to very significant safety in the static analysis.

For the dynamic analysis, we used a real TGV load, which is composed of 15 bogies and 30 axles of 170 kN: the bogies are

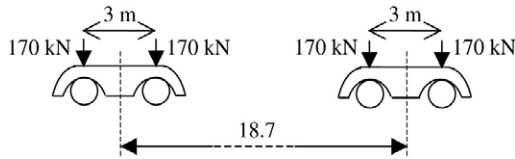


Fig. 7. Two TGV bogies.

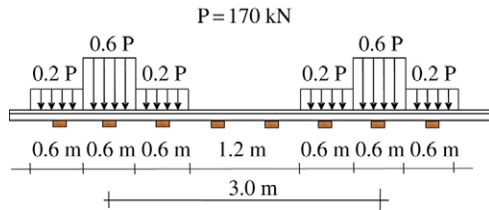


Fig. 8. Distributed load of one bogie.

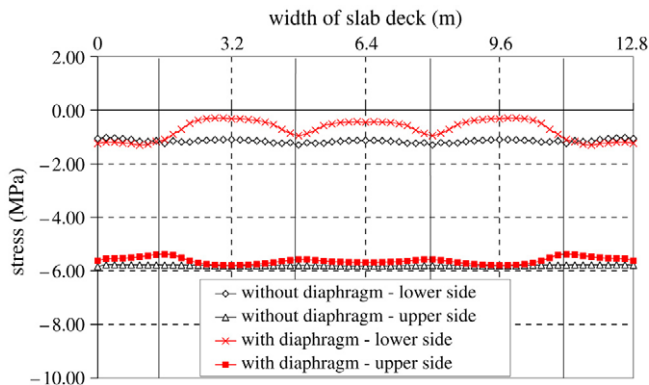


Fig. 9. Longitudinal stress in slab at midspan — self-weight.

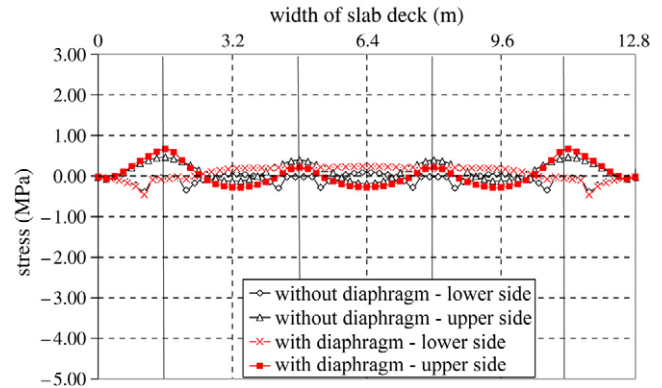


Fig. 10. Transversal stress in slab at midspan — self-weight.

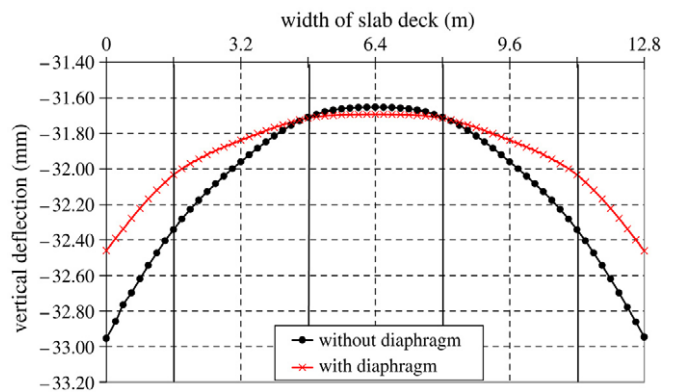


Fig. 11. Vertical deflection in slab at midspan — self-weight.

spaced at 18.7 m from each other and the distance between the two axles of each bogie (two-wheel assembly) is 3 m (Fig. 7). The thickness of the ballast is equal to 0.6 m and distributes the loads (UIC or TGV) on a transverse distance of 2.8 m. In the longitudinal direction of the structure, it distributes the wheel impact on three sleepers over 1.8 m. Thus, these structural bridge considerations enable us to transcribe the TGV loads as distributed loading (Fig. 8).

### 3. Influence of the diaphragm in static and failure analyses

#### 3.1. Self-weight

The weight of the structure itself is very significant: it is composed of the self-weight of the girders, the concrete slab, and the ballast (305 kN/ml). Under self-weight, the bridge deflection is pure longitudinal bending. The composite structure is then very powerful; as the concrete is completely compressed and the vertical deflection is about 3 cm with or without the diaphragm, there is no significant change in terms of deflection and stress (Figs. 9–11).

#### 3.2. UIC loading

Without the diaphragm, under a UIC load and self-weight, the concrete is subjected to tensile stresses, on the under-

side, located between the two loaded girders (Figs. 12 and 13). Only the concrete takes the transverse bending moments, which leads to the appearance of under-side micro-cracks and more significant compression stresses on the top-side face. So as to determine the deflection, only vehicle solicitations are applied to the bridge. Whether the diaphragm is present or not does not make any significant difference to the vertical deflection slab at midspan. The transverse behaviour of the concrete slab is linear with the diaphragm, which corresponds to the assumption of an infinitely rigid diaphragm according to Courbon [15]. Courbon's theory gives a transverse distribution of UIC load on the four girders of 19/40P, 13/40P, 7/40P and 1/40P; this simple method gives very good estimations.

Without the diaphragm, the slab is less rigid and a small inflection occurs (Fig. 14). In this case, Guyon–Massonnet–Bareš's theory [16], based on the orthotropic plate model, must be more relevant than Courbon's theory. As can be seen in Fig. 14, Guyon–Massonnet–Bareš's theory is slightly less precise than Courbon's theory, since the transversal rigidity is given by the bridge deck alone. With and without the diaphragm, the bridge deck can be considered to be endowed with infinite transversal rigidity.

#### 3.3. TGV loads

The real TGV load is lower than UIC, so the stress and the vertical deflection are less significant. With or without the

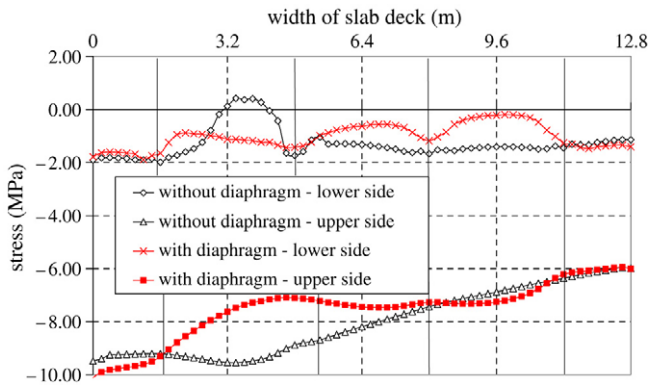


Fig. 12. Longitudinal stress in slab at midspan — UIC.

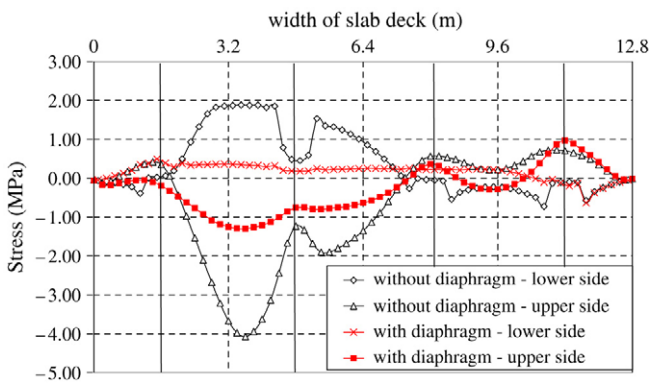


Fig. 13. Transversal stress in slab at midspan — UIC.

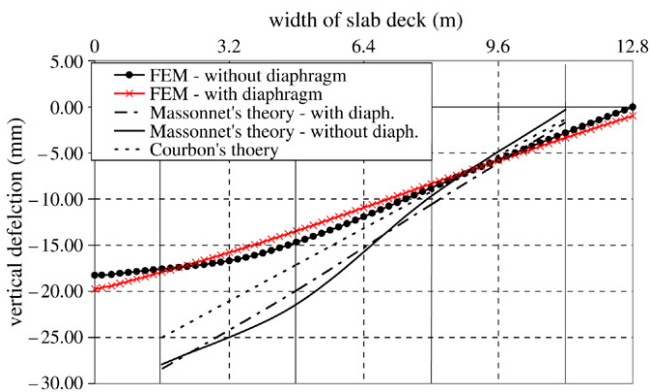


Fig. 14. Vertical deflection in slab at midspan — UIC.

diaphragm, the longitudinal stress (Fig. 15) and the vertical deflection (Fig. 17) are identical. The contribution of the diaphragm to the transverse bending moment is not important. The transverse stresses are about 1 MPa (Fig. 16). The vertical deflection created by the TGV is about 2.5 mm under the track, whereas that created by the self-weight is ten times greater. With or without the diaphragm, the response of the bridge matches Courbon's theory (Fig. 17).

The diaphragm preserves the orthogonality of the flanges and the web girder sections (Fig. 18). Without the diaphragm, the girder webs were subject to a very small rotation (Fig. 19) (the horizontal deflection is 10 times smaller than the vertical

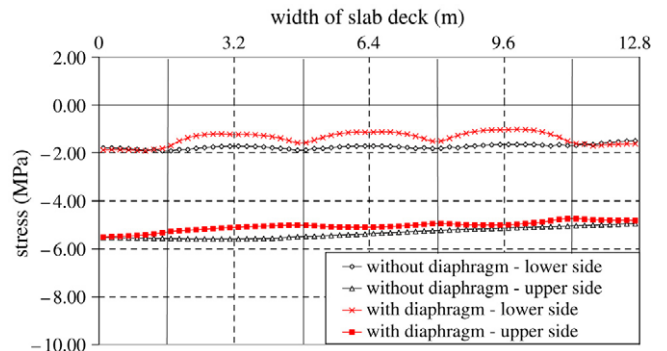


Fig. 15. Longitudinal stress in slab at midspan — TGV.

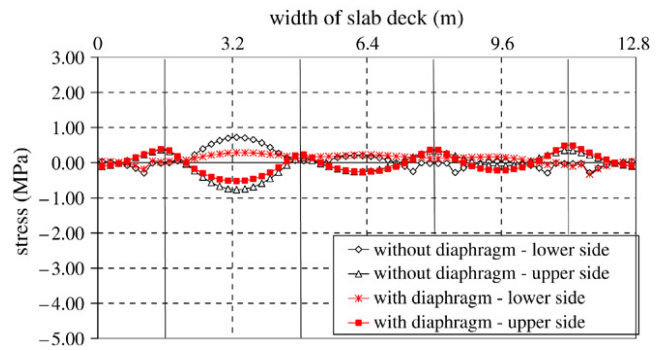


Fig. 16. Transversal stress in slab at midspan — TGV.

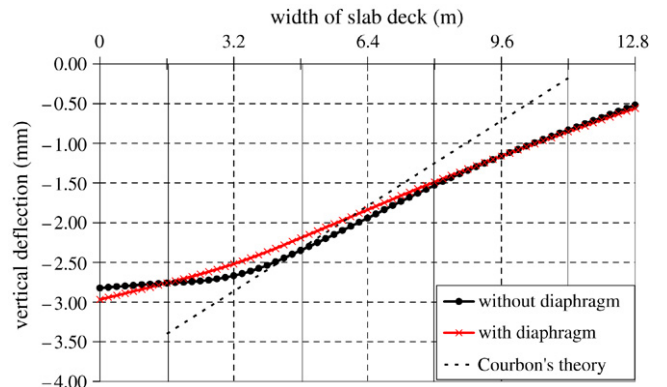


Fig. 17. Vertical deflection in slab at midspan — TGV.

deflection). However, although no risk of the beams swaying is noted for a TGV load, it can be interesting to limit web rotations for more significant loads. With this intention, the replacement of the diaphragm by a simple web stiffener permits the orthogonality of the sections to be maintained.

### 3.4. Static failure

For a better understanding of the contribution of the intermediate diaphragm, we increased the loading up to rupture. We used the “modified Riks method” to perform the collapse; this method is useful to solve ill-conditioned problems such as limited load problems. We have increased the load

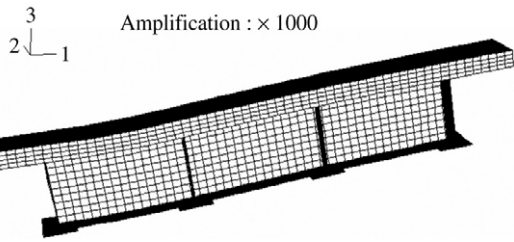


Fig. 18. Deformed shape at midspan with the diaphragm — TGV.

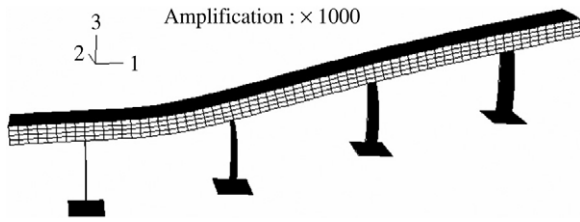


Fig. 19. Deformed shape at midspan without the diaphragm — TGV.

corresponding to the TGV so as to determine the ultimate load (Fig. 20). Without the diaphragm, microcracking appeared in the transverse direction for a load equivalent to three TGVs, and the rupture happened for a load equivalent to 19 TGVs. The rupture is situated in the reinforcement of the concrete at midspan. With the diaphragm, the beginning of microcracking occurs for 12 TGVs. Transverse tensile stresses occur in the concrete and also in the diaphragm. Thus, the rupture is not located in the slab but in the bearing girders: the stresses in the girders attain the plastic limit in the longitudinal direction for a load equivalent to 20 TGVs.

Normal loading uses the bridge at only 5% of its ultimate resistance. That is why the influence of the intermediate diaphragm is not significant.

These static analyses enable us to conclude that, under a TGV loading, the diaphragm can be removed. However, it would be preferable to know precisely the type of convoy

that will travel on the bridge. Indeed, without the diaphragm, tension cracks in the slab deck occur under heavy railway traffic. This can involve a risk of corrosion of the reinforcement, and may decrease the long-term performance of the slab.

#### 4. Influence of the diaphragm in modal analysis

Modal analysis enables us to know the natural frequencies of the bridge system. Moreover this analysis gives the critical speeds of a TGV at which resonance vibration may occur. The resonance is due to two reasons: repeated actions of axial loads and high speed itself [17]. As the record speed of the TGV in France is about 500 km/h, we only study natural frequencies giving critical speeds below this limit. The distance between two bogies is equal to 18.7 m and the speed of the TGV corresponding to a frequency of excitation of the wheels is:

$$V = \frac{18.7 \times f \times 3.6}{i} \text{ (km/h)} \quad (i = 1, 2, 3, \dots).$$

With a diaphragm, the number of acceptable natural frequencies is two, whereas, without a diaphragm, the number is six (Table 1). The absence of a diaphragm increases the risk of resonance. The four supplementary modes have almost the same frequency, and they show the girders' vibration modes. Three-dimensional (3D) modelling is thus necessary in order to represent these vibration modes realistically. With and without a diaphragm, the first mode is the same and corresponds to the first flexural longitudinal (symmetric) mode of the slab deck and the girders.

The excitation of the bridge under the first mode is significant because of the bend slab deck (Fig. 21). We can expect the deflection under the passage of the TGV to be important. The passing of a train moving at a speed of 209 km/h (corresponding to the frequency of the first mode) could not only deteriorate passenger comfort but also lead to ballast destabilisation.

The second mode with a diaphragm is the first torsional symmetric mode of the whole structure (Fig. 22). However,

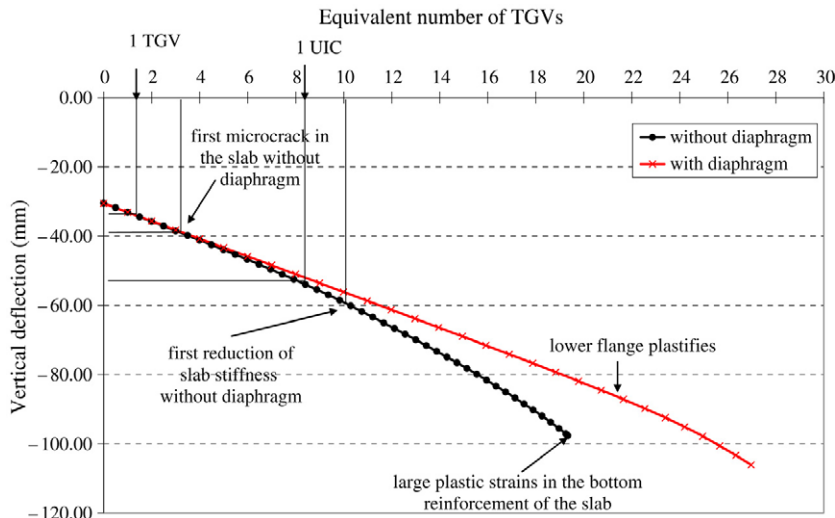


Fig. 20. Vertical deflection in the slab with TGV load equivalent.

Table 1  
Value of natural frequency

Mode	With diaphragm		Without diaphragm		With web stiffener	
	Frequency (Hz)	Critical speeds (km/h)	Frequency (Hz)	Critical speeds (km/h)	Frequency (Hz)	Critical speeds (km/h)
1	3.10	209	3.10	209	3.12	210
2	4.41	297	4.32	291	4.42	298
3			4.42	297		
4			4.46	300		
5			4.51	304		
6			4.59	309		

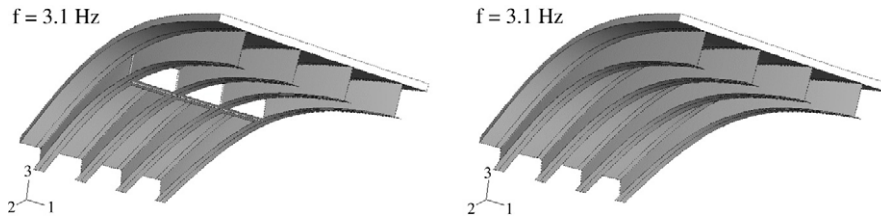


Fig. 21. First flexural mode of the bridge with and without diaphragm at the centre.

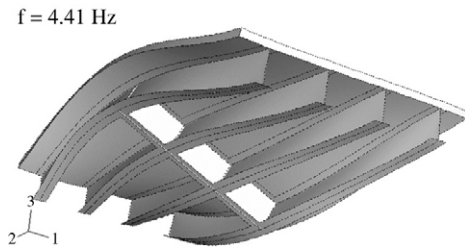


Fig. 22. First torsional mode of the bridge with diaphragm at the centre.

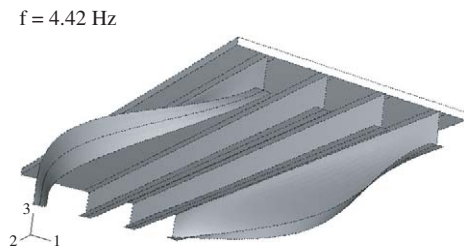


Fig. 24. Second girder mode of the bridge without diaphragm at the centre.

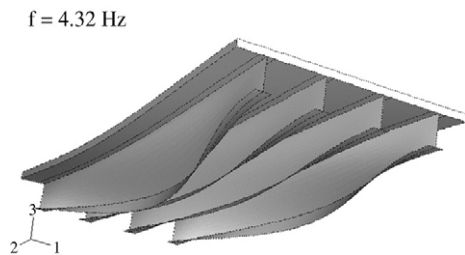


Fig. 23. First girder mode of the bridge without diaphragm at the centre.

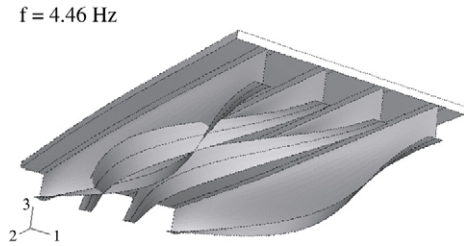


Fig. 25. Third girder mode of the bridge without diaphragm at the centre.

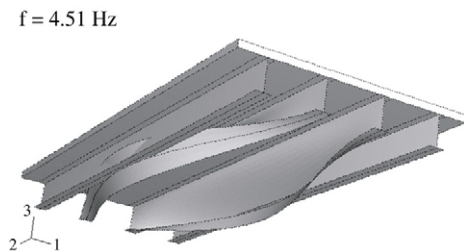


Fig. 26. Fourth girder mode of the bridge without diaphragm at the centre.

the train moves on the bridge on one of the tracks, which is off-centre compared to the centre of the bridge. This creates transversal and also torsional behaviour of the bridge. This mode can be particularly harmful regarding the structure behaviour and it requires a detailed dynamic analysis.

Without the diaphragm, five modes between the frequency of 4.32 Hz and 4.59 Hz appear. In all those five modes, only the girders are excited (Figs. 23–27). The slab deck is never excited, so these modes have no impact on passenger comfort and ballast stabilisation. The girder excitation does not necessarily involve problems like buckling of the webs or swaying. However, these modes can easily be removed by adding vertical web stiffeners in order to stop all elastic instability.

It is impossible to conclude without an analysis of the dynamic behaviour of the bridge in order to understand the influence of the diaphragm on these natural frequencies and,



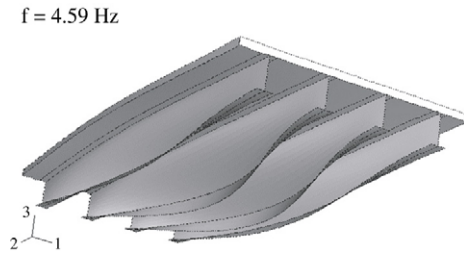


Fig. 27. Fifth girder mode of the bridge without diaphragm at the centre.

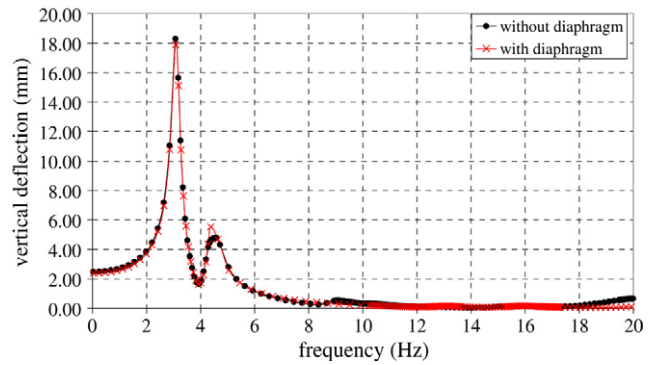


Fig. 28. Vertical deflection with harmonic excitation.

in particular, for the four modes corresponding to girder vibrations.

## 5. Influence of the diaphragm in dynamic analysis

The dynamic response of bridges subjected to the passage of moving vehicles or trains is still a subject of great interest to structural engineers. Previous research on the dynamic response of bridges used by rail cars have been abundant; these studies focus on the modelling of the vehicle. The bridge is always modelled as a simple beam-like structure. The moving-force modelled by a force [18–20] is the simplest way by which researchers can capture the essential dynamic characteristics of a bridge under the action of a moving vehicle, but the interaction between the vehicle and the bridge is ignored. Frýba [17] concluded that the resonance vibration of railway bridges on high-speed lines occurs when the time interval between two successive moving loads is equal to some free vibration period of a beam. Jianzhong et al. [20] showed that the response builds up gradually as the number of moving loads increases. So it is important to model the exact numbers of the moving load corresponding to the wheel of the train being studied. In order to study the vehicle–bridge interaction, various types of sophisticated vehicles are developed, in which a vehicle is modelled as a single-axle or multi-axle mass-spring-damper dynamic system [20,21]. These studies analyse the vibration of a simple beam or multi-span beam [22] under a moving train by using a mathematical formulation based on the Lagrangian approach, and a comparison with the FEM analysis is made. However, this is inadequate to model the response of a multi-girder bridge, particularly under moving vehicles whose paths are not along the centre-line of the bridge.

We use the same mesh and material model as in static analysis. The CPU time is high, whereas the computational process has no divergence problems and just one iteration is necessary for each position of the vehicle. Nevertheless, for a train like the TGV, there are several bogies and the passing of a double TGV in the bridge is very expensive not only in CPU time but also in computer memory storage.

### 5.1. Steady-state dynamic analysis

First, a steady-state dynamic analysis is performed to calculate the response of the bridge subjected to harmonic excitation with the TGV load. In this case, Fig. 28 shows the response amplitude at midspan for the frequencies in the range 0–20 Hz. With and without the diaphragm, the two frequencies

at which bridge resonance occurs are 3.1 Hz and 4.41 Hz. But the harmonic excitation is very different compared to the excitation of the moving vehicle. This simulation extracts the frequencies that need specific analysis with the moving vehicle to know the real response amplitude of the bridge.

### 5.2. Moving-force model

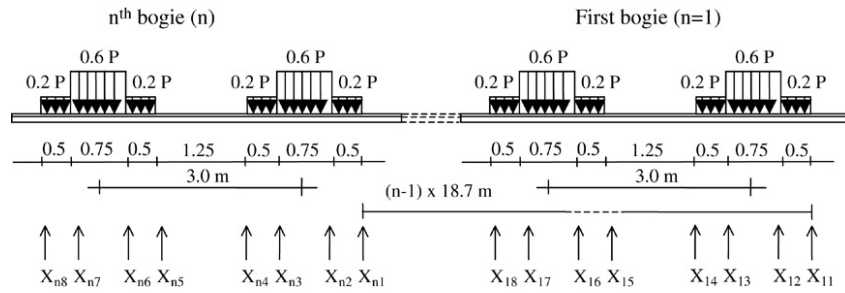
TGV use is very frequent, so the French National Railway Company (SNCF) usually assembles two TGVs to make one train: the double TGV is composed of 30 bogies and 60 wheels. For the vibration investigation, the 60 wheels are transformed into a distributed load travelling along the bridge with a constant distance of 18.7 m between two successive bogies. A subroutine is programmed in ABAQUS to calculate the positions of each wheel on the bridge according to time. All the first bogie distributed load positions are defined precisely and are dependent on the speed of the TGV. The positions of the other bogies depend on the position of the first bogie. At the initial time ( $t = 0$ ), the first distributed load of the first bogie arrives on the bridge. The subroutine is able to determine which loads are on the bridge and where they are (Fig. 29).

### 5.3. Quasi-static analysis

So as to illustrate our subroutine, Fig. 30 shows the load applied to our structure for a quasi-static calculation with the passing of the loads at a speed of 209 km/h ( $f = 3.1$  Hz). We obtain the same vertical deflection at midspan with the subroutine or with the static TGV load. The maximum vertical deflection is obtained when two bogies are together symmetrically on the bridge compared to the centre (2.44 mm): the difference with only one force in the centre is 4%.

### 5.4. Dynamic analysis with moving-force

The general direct-integration method provided in Abaqus/Standart, called the Hilber–Hughes–Taylor operator, is an extension of the trapezoidal rule (Newmark's method). The Hilber–Hughes–Taylor operator is implicit: the integration operator matrix must be inverted, and a set of simultaneous non-linear dynamic equilibrium equation operator matrices must be solved at each time increment. This solution is realised iteratively using Newton's method. A value of 5% is used



$$X_{n1} = V(t) - (n-1) \times 18.7$$

$$X_{n2} = V(t) - 0.5 - (n-1) \times 18.7$$

$$X_{n3} = V(t) - 1.25 - (n-1) \times 18.7$$

$$X_{n4} = V(t) - 1.75 - (n-1) \times 18.7$$

$$X_{n5} = V(t) - 3 - (n-1) \times 18.7$$

$$X_{n6} = V(t) - 3.5 - (n-1) \times 18.7$$

$$X_{n7} = V(t) - 4.25 - (n-1) \times 18.7$$

$$X_{n8} = V(t) - 4.75 - (n-1) \times 18.7$$

With  $V$ : speed of the TGV  
 $t$ : time ( $t = 0$  when  $X_{11}$  arrives on the bridge)  
 $n$ : the number of bogie ( $n=1,2,3,\dots,30$ )

Fig. 29. Position of bogie according to the parameter time.

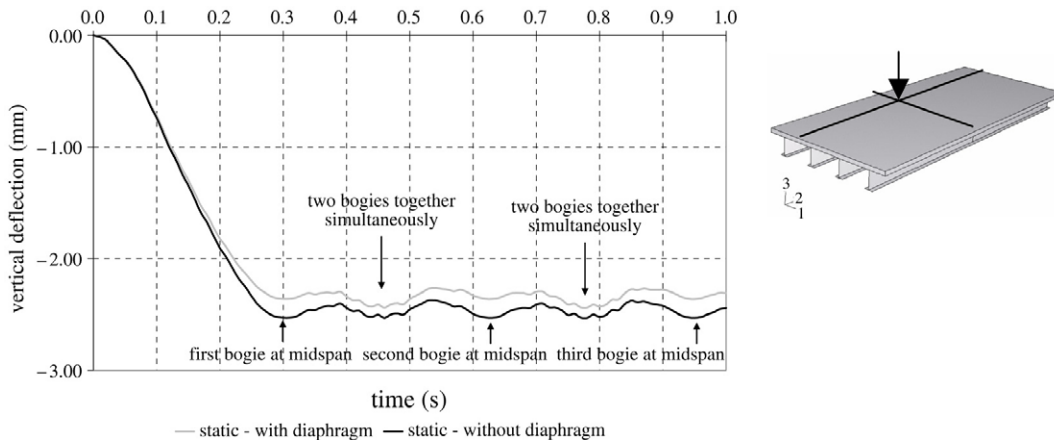


Fig. 30. Vertical deflection at midspan with subroutine and quasi-static calculation.

to introduce artificial damping in this dynamic analysis to obtain an unconditionally stable integration operator. With this numerical damping, the time increment is fixed to catch the maximum amplitude of all the frequencies. A great number of output values are necessary and the time increments must be constant in the step. After some investigations, we conclude that 12 positions for each bogie on the bridge must be calculated to excite the structure and that four of the positions must be stored.

### 5.5. Results for the first bending natural frequency

The vertical deflection under the track at midspan in the slab is a good indicator to determine if resonance occurs. The vertical deflection gradually builds up as the number of moving loads increases and each maximum peak value occurs at the time when the bogie is at midspan (Fig. 31); 30 peak values are obtained. We notice that the response of the bridge is a

maximum when the bogie is in the middle of the bridge and not when two bogies are simultaneously together on the bridge. The maximum response of the structure is obtained when the last bogie of the train is at the midspan of the bridge ( $t = 9.6$  s). The impact factor, defined as  $I_{mp}(\%) = \left( \frac{R_d - R_s}{R_s} \right) \times 100$  by Dongzhou et al. [23] in which  $R_d$  and  $R_s$  are the absolute maximum response for dynamic and static studies, respectively, can be calculated. This impact factor  $I_{mp} = 281\%$  is very important in this case, because the resonance of the bridge gives a dynamic deflection 3.8 time higher than the static analysis. The stresses in the bridge are calculated with the self-weight and the passing of the train. In the longitudinal direction, the whole concrete slab is always compressed and the maximum ( $-6.74$  MPa) occurs when the last bogie is at the midspan. The concrete slab is compressed ( $-0.77$  MPa) on the upper side and in tension ( $0.72$  MPa) on the lower side in the transverse direction. The stresses in the girder are the same as in the

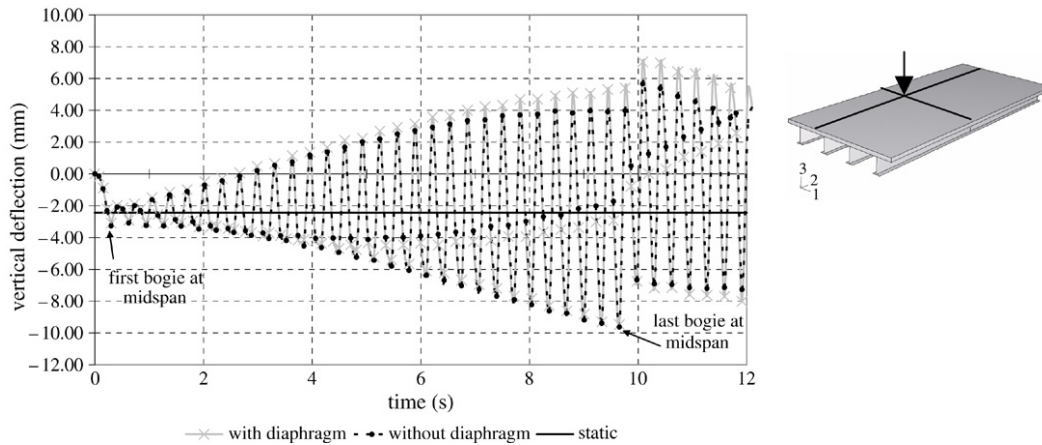


Fig. 31. Vertical deflection under a moving train at a speed of 209 km/h ( $f = 3.1$  Hz).

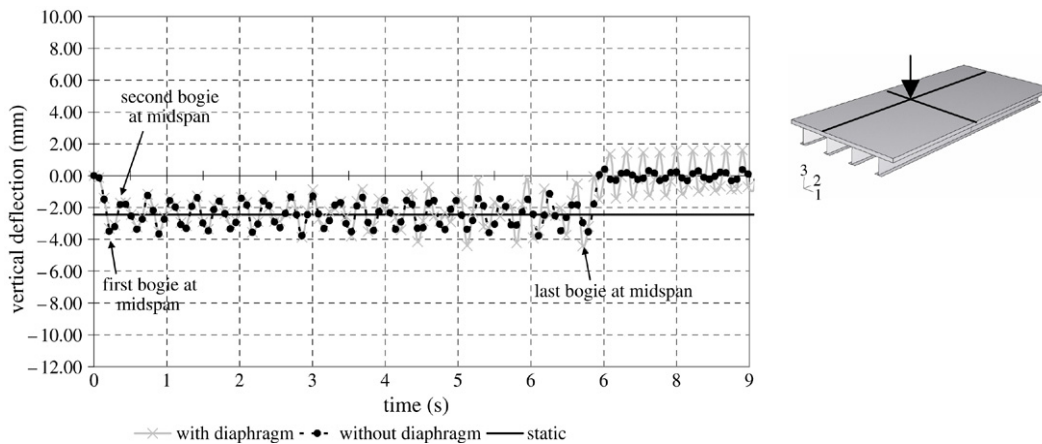


Fig. 32. Vertical deflection under a moving train at a speed of 297 km/h ( $f = 4.41$  Hz).

static analysis. So, the bending excitation does not increase the dynamic stresses in comparison to the static stresses.

With and without the diaphragm, the behaviour of the bridge is practically identical. This is in agreement with the modal study. The diaphragm does not have an influence under an excitation of longitudinal bending, even when the loading is asymmetric.

### 5.6. Results for the first torsion natural frequency

When the train travels along the bridge at a speed of 297 km/h, the bridge is excited at the first torsional symmetric mode when the diaphragm is part of the structure. Without the diaphragm, the excitement happens at one of the girder modes; in these cases, the deflection in the slab under the track at the midspan is not important (Fig. 32). The diaphragm prevents the excitation of the girders under this frequency and transmits it to the slab. At the passage of the 13th bogie, the vertical deflection of the slab slightly increases. At the end of the passage of the train, the factor impact is  $I_{mp} = 81\%$ . The train circulates on one track of the bridge, which is offset from the centre of the structure and induces a small excitation of the slab with

the diaphragm. But this excitation is lower than that obtained with the bending resonance of the first natural mode. In fact, the passage of a train does not enable us to excite the bridge under torsion mode, although the frequency of the bogies is equal to its natural torsion mode. To obtain a resonance of this natural mode, it would be more judicious to simulate two trains on opposite tracks with a small gap between them. However, this configuration is very unlikely and is therefore neglected. Without the diaphragm, no resonance occurs in the slab, even after the passage of the train. The factor impact is  $I_{mp} = 49\%$ . The vibration of the girders has no effect on the slab. The absence of the diaphragm in the structure seems to result in better behaviour of the bridge, which therefore provides a better deflection criterion and better comfort for the passengers. It is, however, necessary to check that the stresses of the girders do not have a significant amplitude without the diaphragm. These verifications are calculated and the maximum amplitude is between 119 MPa and 103 MPa. With the diaphragm, the variation of these stresses is between 129 MPa and 103 MPa. We can then conclude that there no problem of elastic instability in the girders. Under a frequency of 4.41 Hz, the diaphragm is not necessary.

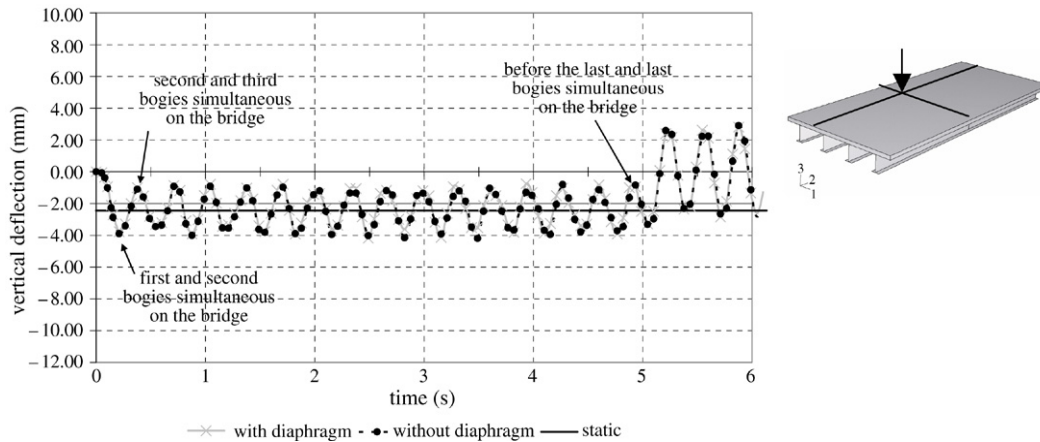


Fig. 33. Vertical deflection under a moving train at the speed of 404 km/h ( $f = 6$  Hz).

### 5.7. Results for ordinary speed (different to critical speeds)

A speed of 404 km/h is selected in order to study the behaviour of the bridge under a speed that is different to the critical speeds. Fig. 33 shows no difference with or without the diaphragm. The first peak value is obtained when two bogies are simultaneously together on the bridge and the peak value period is twice as long as the period for which the bogie moves. No excitation occurs at this speed: with the diaphragm, the impact factor is  $I_{mp} = 69\%$ ; without the diaphragm, it is  $I_{mp} = 65\%$ .

## 6. Influence of the diaphragm under lateral load

Our preceding calculations showed that the diaphragm could be removed on a composite multi-girder railway bridge with a live load. But the diaphragm can have another use, other than the transverse distribution of live loads. Indeed, its influence is very significant in the case of an accidental lateral loading. Road traffic and, in particular, the movement of trucks under the bridge can be at the origin of this accidental load. So, we wanted to know the contribution of the diaphragm under a lateral load. A horizontal load of 1000 kN is applied to the lower flange at the midspan of the structure.

Without the diaphragm, the girder is very much damaged by a lateral load and plastic strains are very important not only on the flange but also on the web. The slab is intact, but the bridge cannot be used any more because one of the carrying elements is damaged. With the diaphragm, the lateral load is distributed on the various girders and the whole structure remains in the elastic range. The bridge does not undergo any damage. The diaphragm provides better resistance in the case of an accidental lateral loading.

## 7. Conclusions

This research considers a composite multi-girder bridge and studies the effects of the intermediate diaphragm through static, modal and dynamic analyses. A method of modelling this type of bridge is developed in order to take into account the mesh in three dimensions and the vibrations of a high-speed train

travelling on the bridge. To study the impact of the diaphragm, a non-linear constitutive equation of the material concrete is used.

The conclusions of this study are:

1. With a static analysis, the diaphragm does not seem to be necessary for this type of bridge.
2. The normal load (TGV) uses this bridge at 5% of its ultimate resistance. This is why the diaphragm has no impact in a static analysis.
3. But, in modal analysis, the absence of the diaphragm increases the number of modes — girder vibration is possible.
4. The presence of the diaphragm has minimal effects on these modal vibrations when a train crosses the bridge at a critical speed. So, it may be possible to not install the diaphragms for these bridges, regardless of their structural contribution. These multi-girder composite bridges would then be more cost effective in comparison to a concrete bridge.
5. However, the diaphragm increases bridge resistance in the case of accidental lateral loading, and also stabilises the girders during construction.

## Acknowledgements

The research reported herein has been sponsored by the France national project MIKTI and the SNCF (French National Railway Company).

## References

- [1] Stevens LK, Gosbell KB. Model analysis of composite beam and slab bridge. Proceedings, Australian Road Research Board 1964;2(2): 1326–43.
- [2] Culham GA, Ghali A. Distribution of wheel loads on bridge girders. Canadian Journal of Civil Engineering 1977;4:57–65.
- [3] Fischer JW, Keating PB. Distortion-induced fatigue cracking of bridge details with web gaps. Journal of Constructional Steel Research 1989;12: 215–28.
- [4] Tedesco JW, Stallings JM, Tow DR. Finite element method analysis of bridge girder-diaphragm interaction. Computers & Structures 1995; 56(2–3):461–73.

- [5] Cheung MS, Jategaonkar R, Jaeger LG. Effects of intermediate diaphragms in distributing live loads in beam-and-slab bridges. *Canadian Journal of Civil Engineering* 1986;13:278–92.
- [6] Chen Y. Prediction of lateral distribution of vehicular live loads on bridges with unequally spaced girders. *Computers & Structures* 1995; 54(4):609–20.
- [7] ABAQUS documentation. version 6.3. Hibbit, Karlsson & Sorensen, Inc.; 2002.
- [8] Zhou S, Rizos DC, Petrou MF. Effects of superstructure flexibility on strength of reinforced concrete bridge decks. *Computers & Structures* 2004;82(1):13–23.
- [9] Zhang X, Sennah K, Kennedy JB. Evaluation of impact factors for composite concrete-steel cellular straight bridges. *Engineering Structures* 2003;25:313–21.
- [10] Wang TL, Huang D, Shahawy M, Huang K. Dynamic response of highway girder bridges. *Computers & Structures* 1996;60(6):1021–7.
- [11] ANSYS documentation. version 5.7 2001. 12th ed. ANSYS Inc.; 2001.
- [12] Lubliner J, Oliver J, Oller S, Oñate E. A plastic-damage model for concrete. *International Journal of Solids and Structure* 1989;25(3): 299–326.
- [13] Lee J, Fenves G. Plastic-damage model for cyclic loading of concrete structures. *Journal of Engineering Mechanics* 1998;124(8):892–900.
- [14] EUROCODES 1. Bases de calcul et actions sur les structures. Partie 3. Charges sur les ponts dues au trafic. ENV 1991-3, October 1997.
- [15] Courbon J. Calcul des ponts à poutre multiples solidarisiées par des entretoises. *Annales des ponts et chaussées de France, mémoires et documents relatifs à l'art des constructions et au service de l'ingénieur* 1940;17:293–322.
- [16] Bareš R, Massonnet C. Le calcul des grillages de poutres et dalles orthotropes selon la méthode Guyon–Massonnet–Bareš. Dunod. 1966.
- [17] Fryba L. A rough assessment of railway bridges for high speed trains. *Engineering Structures* 2001;23:548–56.
- [18] Henchi K, Fafard M. Dynamic behaviour of multi-span beams under moving loads. *Journal of Sound and Vibration* 1997;199(1):33–50.
- [19] Yang YB, Jong-Dar Y, Lin-Ching H. Vibration of simple beams due to trains moving at high speeds. *Engineering Structures* 1997;19(11): 936–44.
- [20] Jianzhong L, Mubiao S. The resonant vibration for simply supported girder bridge under high-speed trains. *Journal of Sound and Vibration* 1999;224(5):897–915.
- [21] Jong-Dar Y, Yeong-Bin Y, Shyh-Rong K. Impact response of high speed rail bridges and riding comfort of rail cars. *Engineering Structures* 1999; 21:836–44.
- [22] Cheung YK, Zheng DY, Cheng YS. Vibration of multi-span non-uniform bridges under moving vehicles and trains by using modified beam vibration functions. *Journal of Sound and Vibration* 1999;228(3):611–28.
- [23] Dongzhou H, Ton-Lo W. Vibration of highway steel bridges with longitudinal grades. *Computers & Structures* 1998;69(2):235–45.