ADVANCED CALCULATION TOOL FOR PAVEMENT DESIGN: APPLICATION TO SURFACING OF ORTHOTROPIC STEEL DECK BRIDGE

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ABSTRACT

This paper focuses on the influence of bituminous surfacing on structural behavior of orthotropic steel deck bridges. Presented research work is part of national "Orthoplus" project, funded by French "Agence Nationale de la Recherche" (ANR). A detailed approach allows taking into account the role of bituminous courses within the global structure behavior. First, behavior of bituminous materials is studied. A linear viscoelastic analysis is proposed, using a rheological model previously developed at the "Département Génie-Civil et Bâtiment" (DGCB) of "Université de Lyon/Ecole Nationale des Travaux Publics de l'Etat" (ENTPE). This model is implemented in a finite element code, allowing for calculation of road structures and particularly, in our case, orthotropic steel deck bridge structures. In order to validate this development, in-situ measurements were performed on two orthotropic structures. Results presented in this paper were obtained from tests on one of them, specifically the Millau Viaduct (tallest and longest multiple-span cable-stayed bridge in the world). In addition, laboratory measurements were carried out, consisting in a five-point bending test. Experimental results and simulation outputs were finally compared.
In the framework of ANR "Orthoplus" national research project (focusing on the evaluation of the interaction between road surfacing and metal structures of orthotropic bridges during design stage), ENTPE, in collaboration with EIFFAGE Travaux Publics, is developing a general 3D linear viscoelastic calculation tool for pavement design. This work, already awarded in 2008 with special "Charles Parey" prize by the French Committee of Permanent International Association of Road Congresses (PIARC) [1] for its theoretical developments, is here completed and validated through the performed challenging experimental campaign, in particular the real-size investigation on the Millau Viaduct.

1. CONTEXT

The study lies within the framework of one of the tasks of national research "Orthoplus" project, funded by ANR, involving EIFFAGE Travaux Publics, Arcadis, "Centre Technique Industriel de la Construction Métallique" (CTICM), Eiffel, ENTPE, "Laboratoire Central des Ponts et Chaussées" (LCPC) and "Service d'Etudes sur les Transports, les Routes et leurs Aménagements" (SETRA). The four-year project will end at the beginning of 2011. Moreover, this work is the subject of a PhD thesis in the frame of a "Convention Industrielle de Formation par la REcherche" (CIFRE) contract between EIFFAGE Travaux Publics, its student-employee, Simon Pouget (hosted by the ENTPE laboratory), and ENTPE.

2. TECHNICAL ISSUE

When self-weight of a bridge is a key parameter for its design optimization (wide span, movable bridge), an orthotropic deck usually represents the best solution. Mechanical behavior of these structures is quite easy to understand, whereas fine modeling of their response is complex. They show high sensibility to fatigue phenomena due to their great flexibility. Because of mentioned modeling difficulties, distresses are usually avoided by adopting safe well-known construction practices. Obviously, such an approach leads to a non-optimized design, albeit satisfactory.

Mechanical behavior of the pavement can be modeled, therefore its influence on global behavior of structure can be taken into account. Surfacing becomes an authentic element of the structure, which can be optimized. This implies a reconsideration of construction practices for non-standard cases. Design of an orthotropic deck could then include not only geometry of spans and girders and thickness of the deck plate, but also properties of surfacing material as well as its thickness. Thus, an entirely new conception of integrated design of the orthotropic deck-surfacing couple becomes more appropriate. It is the big innovation of the Orthoplus project.

Moreover, it is necessary to finalize the set of tools (in terms of theory, procedure and specifications) allowing taking into account the coupling of deck and surfacing for the estimation of life duration of the metal structure and the pavement itself. Indeed, the latter aspect is generally poorly assessed. Premature resurfacing of a heavily trafficked infrastructure results in non-negligible cost and a discomfort for users (a recent example is the Cheviré bridge in the greater Nantes area).

3. DBN MODEL GENERAL FORMULATION

Di Benedetto-Neifar (DBN) model (Figure 1), describes the behavior of bituminous materials, experimentally observed on a wide range of load. This visco-elasto-plastic general law summarizes a Linear ViscoElastic (LVE) behavior in a small strain domain, a non-linear behavior for higher strain levels together and a viscoplastic flow. Temperature effect is well considered for both low and high strain levels [2, 3, 4, 5, 6, 7, 8, 9].

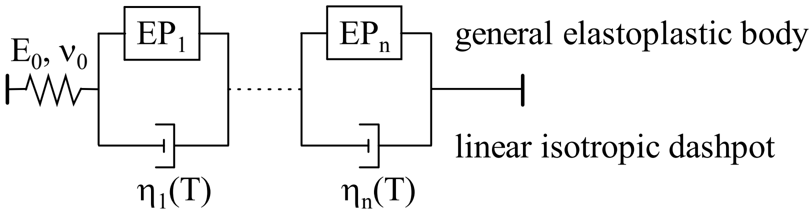

Figure 1 – General DBN model schematic

3.1. Asymptotic LVE formulation (generalized Kelvin-Voigt model)

For small amplitude loads, behavior of bituminous materials is linear. The asymptotic formulation of DBN model (Figure 2), equivalent to a n-element generalized Kelvin-Voigt model, is then used.

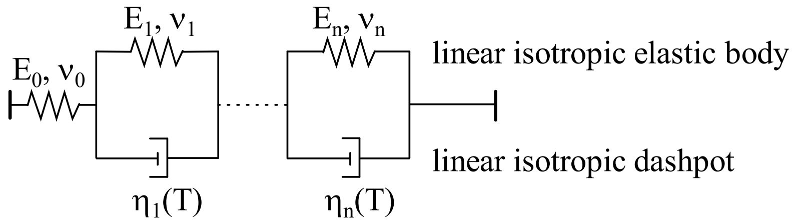

Figure 2 – Asymptotic expression schematic, in the linear domain of DBN model

3.2. Model calibration with Orthochape® mixture

Calibration of linear DBN model was carried out by means of complex modulus tests (Figure 3); during such tests, axial tension/compression loads were applied and axial and radial displacements were measured, together with axial force. The device provides accurate measurements on a wide scale of displacements, allowing performing creep and permanent deformation tests [10, 11]. From this experiment, which is homogeneous in the central measuring area of the sample, complex modulus and complex Poisson's ratio (in terms of norms |E*| and |ν*| and phase angles ϕ_E and ϕ_ν) can be obtained.

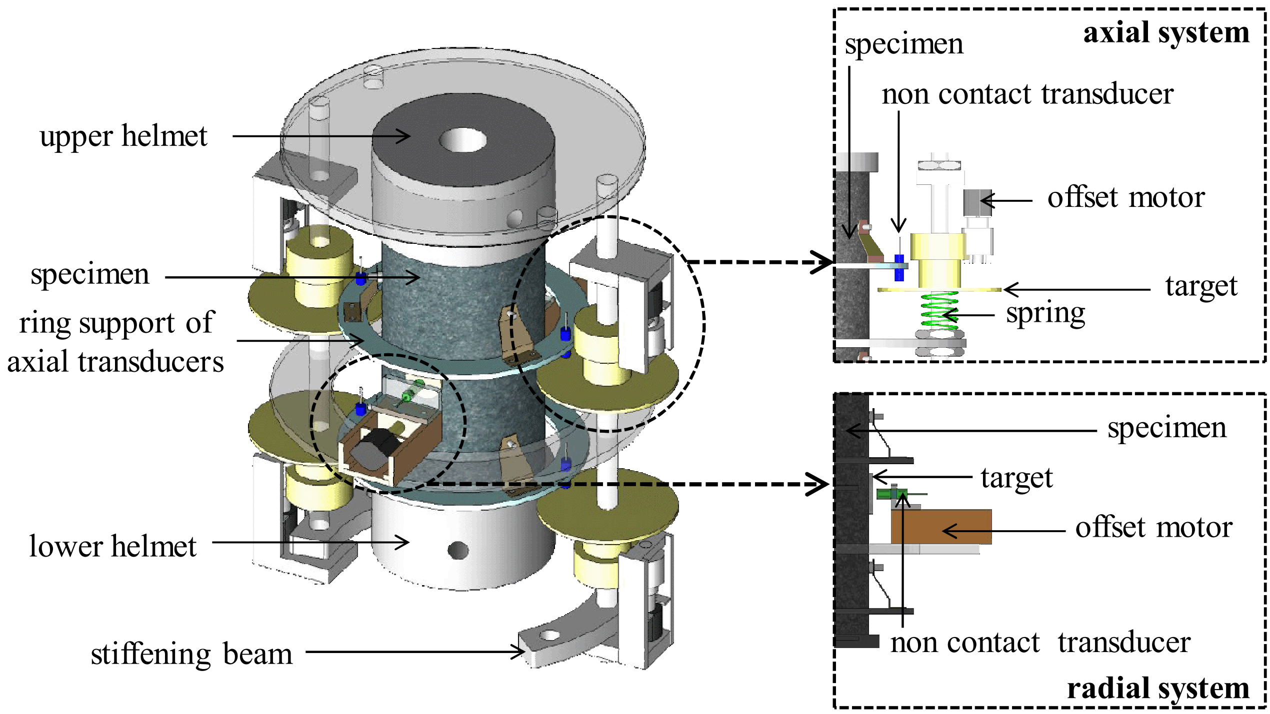

Figure 3 – Device used for complex modulus test

Measurements were made at 9 different temperatures (from -30°C to 50°C), sweeping 7 frequencies from 0.01Hz to 10Hz. Isothermal curves for complex modulus and Poisson's ratio norms (|E*| and |ν*|) are plotted in Figure 4 for Orthochape® mixture, which covers the Millau Viaduct deck. Time-Temperature Superposition Principle (PSTT) [12, 13] allows plotting a unique curve, considering a reference temperature T_{ref}, chosen equal to 10°C, by horizontally shifting each isothermal curve along the frequency axis, using a shift factor a_T (equal for both |E*| and |ν*|). Obtained master curves can be used in a design process.

Then, DBN model can be calibrated in the small strain domain (Figure 2). Calibration of constants (E_i, ν_i, η_i) is achieved through an optimization procedure in the frequency domain using the three-dimensional formalism of 2S2P1D model (2 Springs, 2 Parabolic elements and 1 Dashpot) [5, 8, 11]. Corresponding simulations are plotted in Figure 4. Model simulations accurately fit experimental results.

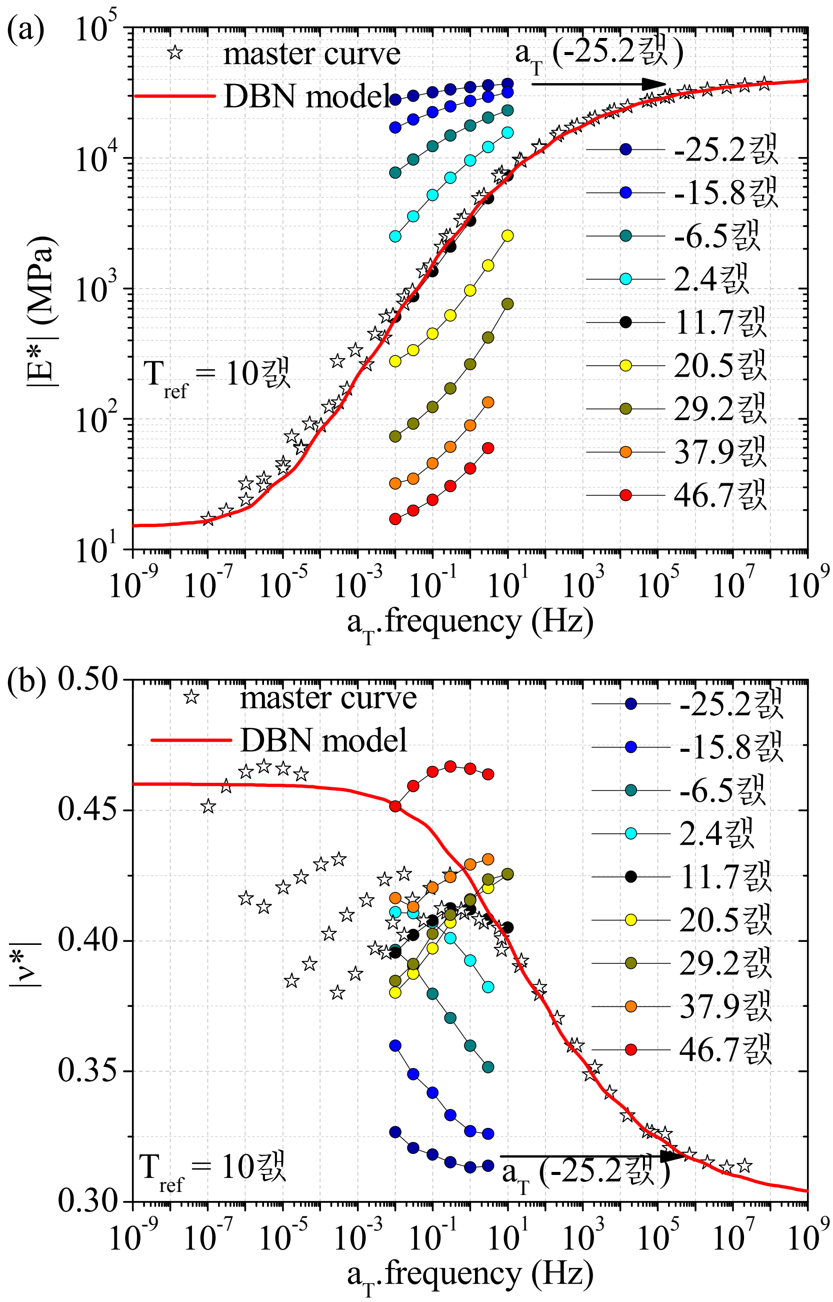

Figure 4 – Experimental results (test Orthochape4), master curves, DBN model (20 elements) (Figure 2) plotted at a reference temperature of 10°C.
(a) Complex modulus norm |E| ; (b) Poisson's ratio norm |ν*|*

4. COMSOL SOFTWARE

Presented finite element calculations were carried out using Comsol software. The linear viscoelastic law, used to describe bituminous mix behavior in the small strain domain, was implemented. The software then becomes a very useful tool for pavement conception and design.

5. CASE STUDIES

5.1. Five-point bending laboratory test [14]

Finite Element Method (FEM) calculations were run on the geometry of the five-point bending fatigue test. After introducing general calculation parameters, obtained results for points A and C (Figure 5) are presented for the different considered configurations: Orthochape® mixture, associated with Parafor Pont® sealing sheet (Siplast group), and BSI Ceracem® High-Performance Fiber-Reinforced Cement Concrete (HPFRCC).

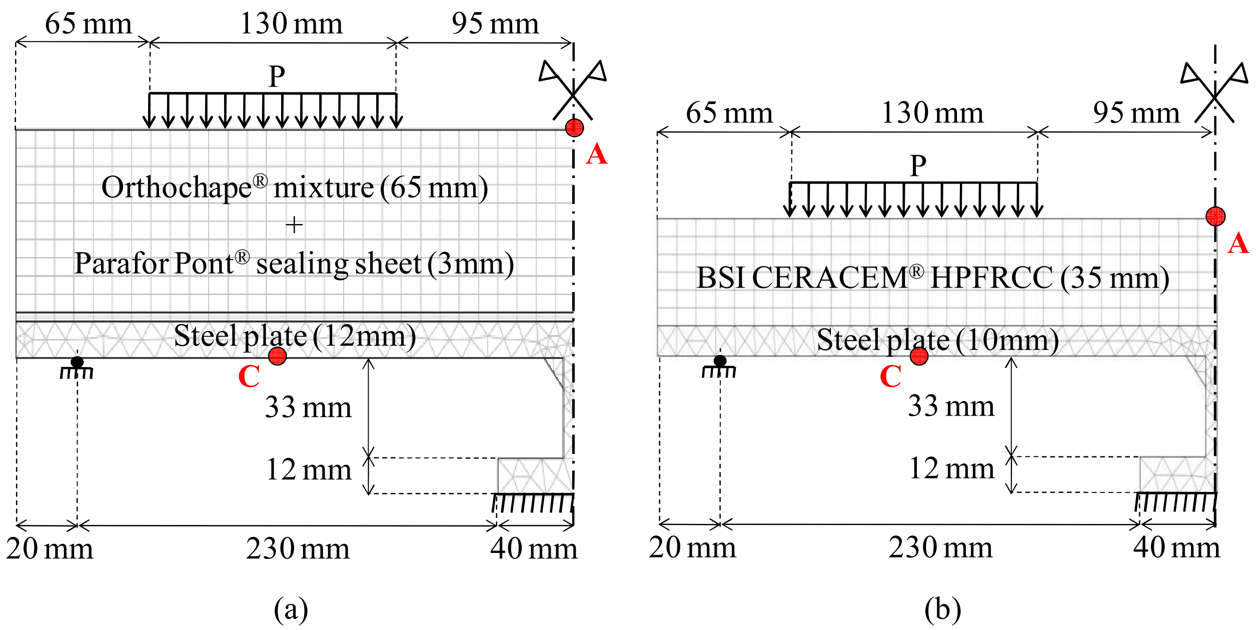

Figure 5 – Geometry, boundary conditions and meshing of a 5-point bending test specimen. (a) Orthochape® mixture; (b) BSI Ceracem® HPFRCC

5.1.1 *Geometry*

Two different designs were studied:

- Specimens with bituminous mix surfacing:
  - 12mm-thick steel plate;
  - 3mm-thick Parafor Pont® sealing sheet, which ensure bonding and waterproofing between surfacing and steel plate;
  - 65mm-thick Orthochape® mix.
- Specimens with HPFRCC surfacing:
  - 10mm-thick steel plate;
  - 35mm-thick BSI Ceracem® HPFRCC.

Perfect bond is assumed between layers.

5.1.2 *Boundary conditions*

The central support of the orthotropic structure is a full-moment connection. Other supports are simple, allowing for horizontal movement. *P* is a 4 Hz sinusoidal compressive load, varying between 0,067 MPa and 0,67 MPa [16].

5.1.3 *Material behavior*

Isotropic LVE (ILVE) behavior is assumed for the two bituminous materials (asphalt mixture + sealing sheet) [1, 10, 11, 15, 17, 18, 19, 20, 21]. Correct simulation is ensured by implementation of DBN model in the Comsol software.

Isotropic Linear Elastic (ILE) behavior is assumed for HPFRCC (E_{HPFRCC} = 65 GPa and ν_{HPFRCC} = 0,2) and steel (E_{steel}= 210 GPa and ν_{steel} = 0,3).

5.1.4 *Results*

Figure 6 shows comparisons between stress-strain curves obtained considering a HPFRCC surfacing (ILE behavior) and a Orthochape® + Parafor Pont® surfacing (ILVE behavior). It presents results for point A on the surface of wearing course, aligned with the centerline of the supporting beam, where maximum tension stress are supposed to occur. At first, a significant difference between maximum stress levels achieved in the HPFRCC (around 7 MPa) and in the mixture (ranging from 0.5 MPa at 30°C and 3 MPa at -10°C) can be observed. Stress-strain curves within the mixture appear to be strongly dependant on temperature, as expected. Moreover, contrarily to HPRFCC case, which is always in tension, calculated stress in the bituminous surfacing oscillates between tension and compression after a certain number of loading/unloading cycles (depending on temperature).

Comparison between calculations and experimental results at 30°C is proposed in Figure 7 for bituminous materials surfacing described in Figure 5(a). Strain generated by average value of *P* sinusoidal compressive load, is plotted versus time at points A and C (Figure 5). It can be observed a rapid stabilization of strain in steel plate at point C. However, in bituminous mixture at point A, strain evolves from extension to contraction as previously observed in Figure 6.

This example shows the importance of taking in to account viscous aspects of bituminous material behavior in the calculation of pavement structures. This is also valid in cases like the presented one, where bituminous surfacing is applied over metal bridge structures

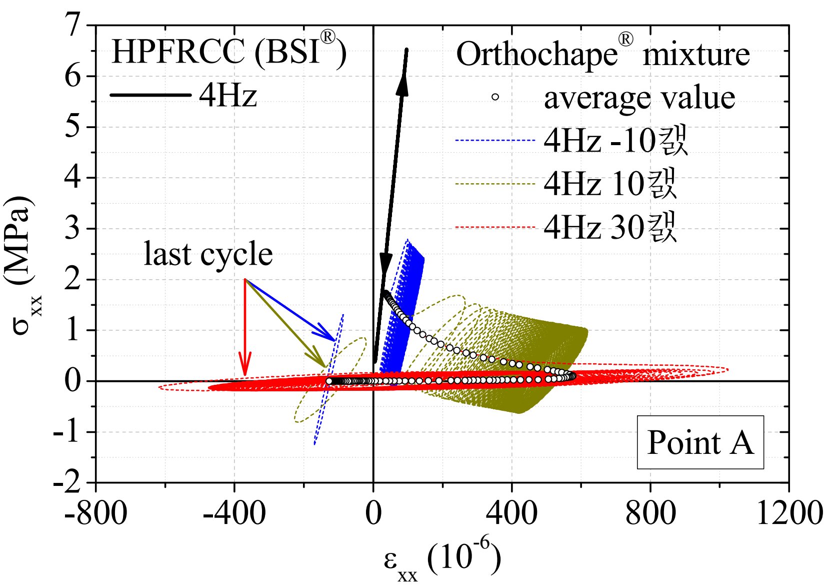

Figure 6 – Stress-strain curves obtained at point A on top of surfacing at 3 temperatures -10°C, 10°C and 30°C from calculations on the five-point bending structure

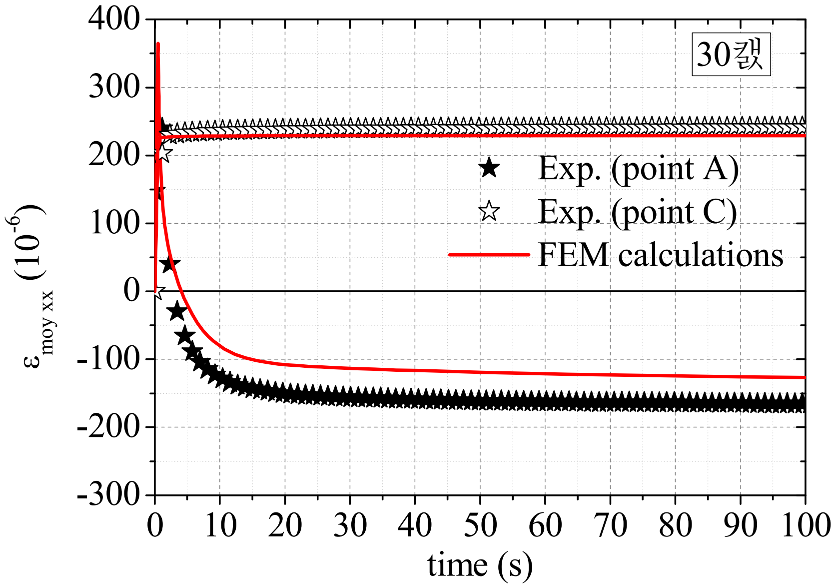

Figure 7 – Calculated average strain $\varepsilon_{moy\ xx}$ versus time and comparison with experimental results at 30°C at points A and C (Figure 5)

5.2. In-situ measurements: the Millau Viaduct

The most impressive studied orthotropic structure during "Orthoplus" project is the Millau Viaduct (tallest and longest multiple-span cable-stayed bridge in the world). In this paper, in-situ experiments are described. Analysis of data was performed using Finite Element Method (FEM). Results are compared with experimental data, to show capabilities of the developed calculation tool [20, 21].

5.2.1 *Experimental study*

Experiments consisted in loading the Millau Viaduct and measuring corresponding strains with a net of gauges.

The objective was to load slow and emergency lanes. The whole bridge slow lane (South → North direction) was secured using signposting during a half-day. Loading was applied by a truck and its trailer; for a total of 38.1 tons distributed on five axles (Figure 8). Each axle was precisely weighed and footprint of each tire was recorded.

First, static tests were performed. The truck was precisely positioned on the bridge. Location of the most loaded axle (second one of the tractor truck, with two twin wheels) is indicated by dx and dy (Figure 9). This axle was located on two different dy longitudinal positions, initially over a crossbeam (dy=16.7m) and then equally distanced between two crossbeams (dy=14.6m). Nine different transversal positions dx were tested, so that one twin wheel of the axle was always located over stiffener n° 6, 7 or 8.

Secondly, tests under wheel load were performed. The truck travelled a 40 m-long distance over the instrumented area at two constant speeds 10 and 50 km/h in order to underline viscous aspects of bituminous material behavior. Tests were carried out for different transversal positions dx. Positions were chosen as close as possible from the considered ones during static loading. 24 tests under wheel load were realized.

Ambient temperature was between 12.1°C and 12.3°C.

Figure 8 – Pictures of the Millau Viaduct during tests. (a) Truck during axles weight; (b) View of the bridge; (c) Loading truck on the Millau Viaduct; (d) Stiffeners and crossbeams with gauges

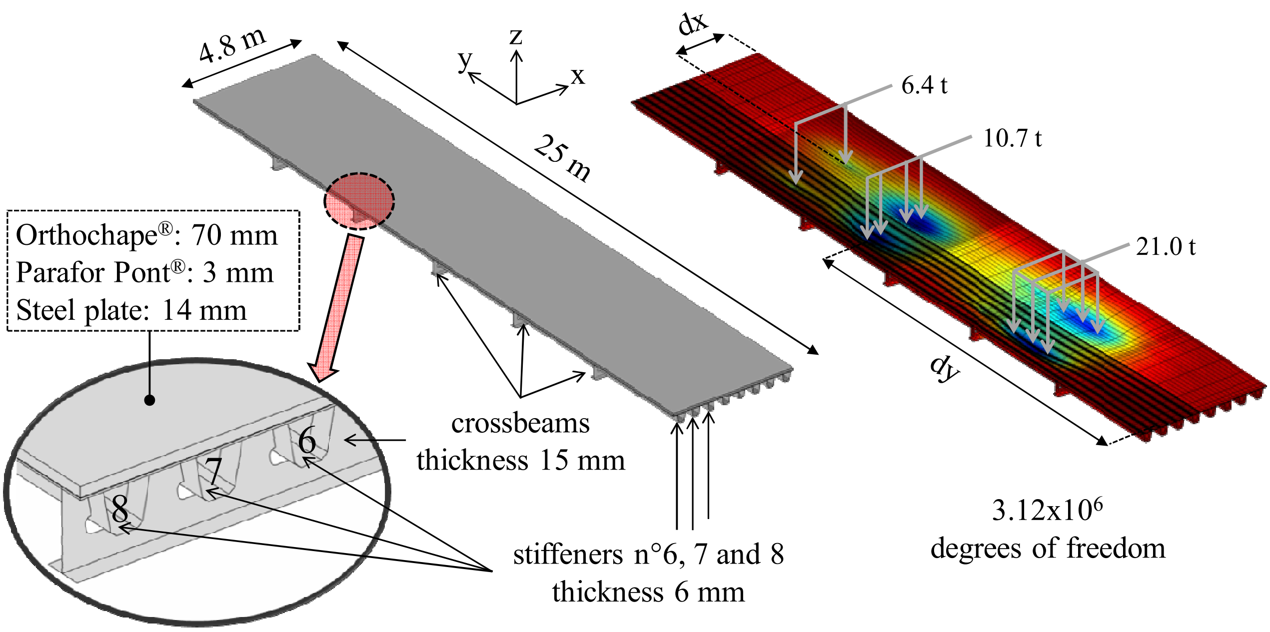

Figure 9 - Geometry, mesh, load and vertical displacement field of the Millau Viaduct structure in the Finite Element Code

Two longitudinal locations were chosen to monitor strains in the steel deck, one between two crossbeams and the other one on a crossbeam (same as for static loading). Chain gauges were glued under the deck around stiffeners n° 6 and 7 (two per stiffener) to obtain information on the stress field around welding lines (Figure 10). Some bi-directional gauges are also glued below the deck between and under stiffeners n°5, 6, 7 and 8 (Figure 10). Others gauges are used but not detailed here.

Concerning static loads, transversal strain (ε_{xx}), measured under steel plate, between two crossbeams, are presented in Figure 10(a) for one longitudinal position (dy=14.6m) and one transversal position (dx=1.77m) of the truck. Each data point represents the average value of strain after stabilization. Example of measured longitudinal strain (ε_{yy}) under stiffener 7, between two crossbeams, during loading at 50km/h, transversally located at dx = 1.82 m, is also proposed in Figure 10(b). Data are compared with calculation results.

5.2.2 *Analysis with FEM calculations*

3D Finite Element calculations (FEM) are performed to simulate the experimental campaign on the Millau Viaduct. Due to complexity and size of the structure, some simplifications are necessary (Figure 9):

- 6 similar elements are considered longitudinally.
- slow and emergency lanes are modeled, for a total of 8 stiffeners.
- crossbeams are completely supported on one extremity (near stiffener n°8) to represent actions of the rest of the bridge structure.
- steel plate, sealing sheet and bituminous mix surfacing are modeled with 3D brick elements while crossbeams and stiffeners are modeled with 2D shell elements. Mesh is refined around stiffeners n° 6, 7 and 8, inducing 3.12 millions degrees of freedom.
- wheel loads are modeled by rectangular loaded surfaces.
- ILE behavior is assumed for steel (E_{steel}= 210 GPa and ν_{steel} = 0,3). ILVE behavior is assumed for the two bituminous materials (asphalt mixture + sealing sheet). Correct simulation is ensured by implementation of DBN model in the Comsol software.

Some simulation results are presented in Figure 10. Discontinuities appear in the curve, due to the presence of stiffeners and the way they are modeled with 2D shell elements. Comparisons with experimental data show reasonable agreement, taking into account errors in locating truck and gauges.

6. OUTLOOKS

In the framework of ANR Orthoplus national research project (focusing on the evaluation of the interaction between road surfacing and metal structures of orthotropic bridges during design stage), ENTPE, in collaboration with EIFFAGE Travaux Publics, is developing a general 3D linear viscoelastic calculation tool for pavement design.

DBN model has already been implemented in a FEM calculation software for pavement design, particularly for bridge surfacing application and in general for every structure including materials characterized by a viscous behavior. This tool is already in use by ENTPE and EIFFAGE, but is aimed at a wider diffusion, also for French and international communities in the road business.

More work is still needed to finalize this method, especially introducing 3D general DBN model, taking into account fatigue, rutting, etc…

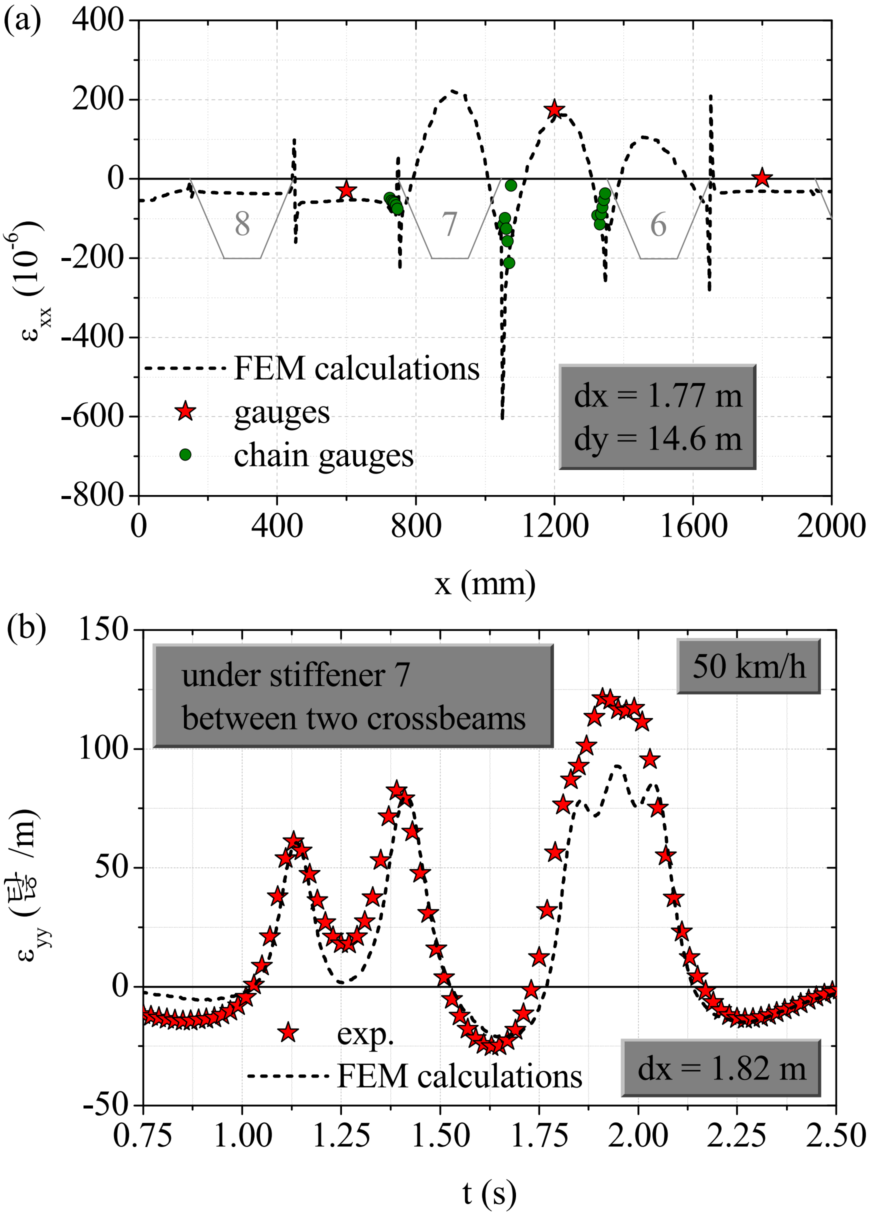

Figure 10 - Comparison between measured strains and FEM strain calculations.
(a) static load test - ε_{xx} for dx = 1.77 m and dy = 14.6 m
(b) wheel load test - ε_{yy} under stiffener 7 in the middle of two crossbeams for dx = 1.82 m at 50km/h

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