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BRIDGE-TRUCK INTERACTION: SIMULATION, MEASUREMENTS AND LOAD IDENTIFICATION

W. Baumgaertner

ABSTRACT

Based on a commercial finite element (FE) program, a method was developed to perform simulations of truck models crossing a bridge. The simulation is divided into three sections: truck on road before the bridge, on the bridge, and on road after the bridge with the bridge vibrating without the truck. Bridge and truck are represented as spatial FE models. The roughness of the lanes can be modeled based on power densities or on measurements. Results of simulations (deflections of bridge and truck structures, contact forces, strains) are presented for a 3-axle instrumented truck crossing a calibrated 2-span box girder bridge.

When a calibrated bridge model is simulated, results as influence lines can be used to establish a relationship between axle load and strains at defined points where measurements are intended. Accurate influence lines, (adapted for example for the influence of dynamics on measurements) are very important for the carrying out of accurate weigh in motion calculations of truck loads using bridges (B-WIM).

1 INTRODUCTION

Some current problems for engineers concerned with dynamic reactions caused by moving heavy vehicles on substructures are the deterioration effects in the ballast caused by high speed trains (e.g. ICE in Germany), the behaviour of new slab track structures for railways, and the road-friendliness of truck suspensions. In all cases, the dynamic contact forces and the reactions in vehicles and substructures are of particular interest with regard to deterioration (e.g. Cole & Cebon 1996).

The preferred type of model for simulation techniques depends on the „type“ of engineer. A civil engineer is accustomed to using a simple vehicle model as he/she is experienced in bridge, road and soil models. A mechanical engineer is familiar with model suspensions and nonlinear behavior of vehicles combined with simple structures. More cooperation should be initiated to make best use of the experience in both fields of activity.

A numerical simulation method is in use at our institute for several years based on a commercial FE program. Particularly with respect to measurements in a bridge and a truck, this method can provide strain, force and acceleration curves by time to be compared to measured records and to derive relationships between truck and strain at different structural locations.

Measurements with pre-weighed trucks were effected at the Belleville bridge (France) as part of the European Research project named *WAVE* (Weight-in-motion of Axles and Vehicles for Europe) to estimate the gross weight and axle loads of trucks using special methods. Numerical simulations were performed to obtain a better understanding of the measured responses, such as strain records for the steel box and the concrete plate, and to obtain a possibility to calibrate measured strains with respect to truck and axle loads.

A recent description concerning the European activities in developing weigh-in-motion methods using bridges is given by O'Brien et al. (1997).

2 BRIDGE AND TRUCK MODEL

Bridge Belleville/France

The bridge of concern is a box girder with a concrete slab with spans of 54.9 m and 51.7 m and is the access bridge to a longer bridge named Belleville bridge in France ([Figure 1](#)) with a similar cross section.

Measurement of strains and accelerations under traffic were performed in order to calibrate the FE model of this bridge and to study load identification methods with respect to the *WAVE* project mentioned above.

The FE model was mainly developed, calibrated and tested as part of the diploma project of Penka (1997) and Montgobert/Roullier(1997). The modeling of the stiffening elements in particular was difficult as the available information was little. With respect to a simulation with several thousand time steps, the model with about 2000 degrees of freedom (DOF's) is not very detailed but is able to reproduce the significant eigenfrequencies. Two mode shapes of the bridge model are presented in [figure 2](#). The adaption of the stiffness of the finite elements was performed with respect to measured accelerations (eigenfrequencies) and strain measurements at different locations (mode shapes). The animation of the calculated mode shapes can help a lot in developing an understanding of the dynamic behaviour, especially of the higher modes.

Three-axle truck (VTT Finland)

The truck model was developed based on a particular three-axle truck belonging to VTT, the technical research center of Finland. This truck is instrumented with strain gauges and accelerometers so as to measure dynamic wheel loads.

The FE model was established as part of the diploma project of Kellner (1997) in Finland in accordance with the known data of the truck. Beam elements were chosen to describe axles and body. Spring and damper elements describe the suspension. The mass is distributed in the beam elements and in single masses attached to the beam nodes (e.g. to replace rotational inertia). The resulting static wheel loads coincide with the measured ones.

Eigenmode	Frequency (Hz)
frame twist	0,82
body bounce	2,01
body pitch	1,02
body roll	1,53
front axle: hop	11,08
front axle: roll	15,50
second axle: hop	9,89
second axle: roll	13,25
third axle: hop	9,97
third axle: roll	13,26

Table1: Truck modes and frequencies

3 INTERACTION CALCULATION METHOD

There are several techniques and levels of modeling in use to calculate the dynamic reaction of subsoil or bridges due to the crossing of trains or trucks. With regard to interaction effects and changing contact points between wheels and lanes, there are no closed solutions when the truck is modeled as a vibrating system including mass and elasticity. Basic solutions are discussed in Fryba (1968). In most cases, the structure is modeled as a simple Euler Bernoulli beam with a truck modeled as a multi-body system. It is usual to limit the degrees of freedom as a lot of time steps have to be calculated numerically. The system of differential equations can be solved with the Runge-Kutta method. This approach is very helpful for studying the influence of different structural parameters. On the other hand the modeling of complex structures is restricted, although this is necessary when measured records of real structures have to be explained.

Mostly the FE method is used for civil engineering problems, such as looking for maximum stress, deflection or dynamic reactions of bridges. For our task, this results in a high number of DOF's with a corresponding long calculation time. The main advantages are, especially with commercial FE program systems, that pre- and post-processing software is available for modeling and for the explanation of results which can be very difficult for real structures. The animation of the results can be very helpful, e.g., to explain time varying effects or to investigate maximum strains at different locations. Recently large commercial programs based on multi-body systems, mainly utilized in the automotive industry for complex simulations, offer FE extensions.

The method we are using to calculate interaction is based on FE software, basically described by Cifuentes (1989). The bridge as well as the truck are modeled separately and can be tested in advance with regard to frequencies and mode shapes (see [figures 3](#), 2 and table 1). This is very helpful to check the input and to test the accuracy of the derived models with respect to real structures. The interaction is allowed for by the inclusion of additional geometric equations for the contact points and contact forces as Lagrange parameters (Baumgaertner & Fritsch 1995). With this technique, the large structural matrix has not to be changed during the calculation, but an iteration for equilibrium has to be performed for each time step, similar to nonlinear calculations. As a large quantity of additional complex information for each contact point between wheel and lane has to be provided for the FE software, a new software tool (Lichte 1996) was developed. In particular, the roughness of the surface and local gaps (e.g. joints), as the main cause for dynamic excitation, can easily be adjoined. The dynamic effects of the rotation of the wheels and nonlinearities of the suspensions are (until now) not included.

For practical use we perform the calculation for three different situations:

- a) truck is running on the (rough) road before reaching the bridge, the truck is coming to the bridge in a steady vibrating state,
- b) the truck is crossing the bridge with rough surface, both systems are interlinked at different points according to speed and chosen time steps,
- c) the truck has left the bridge, the bridge is in a free vibrating state (only eigenfrequencies, mixture of mode shapes), the truck is running on the (rough) road.

4 RESULTS OF NUMERICAL SIMULATIONS

In this section selected results are presented using the models as described in sections 2 and 3. The length of the road before the bridge was chosen as 20 m and after the bridge as 73.4 m. With a chosen speed of 20 m/s the front wheels of the truck reach the bridge after 1 s, the pier after 2.75 s and the end of the bridge after 6.33 s as marked in the figures.

The roughness was modeled according to power densities for motorways of good and medium to bad qualities. Samples were calculated with little and no damping of the bridge to study this influence.

The simulation was performed with 10 000 time steps, each step corresponding to a length increment of 0.02 m. The calculations were carried out on a Pentium PC120MHz (time for calculation about 2 h) and as remote jobs at the central computers of our university.

4.1 Strains, forces and deflections by time

Strain curves by time at different locations were evaluated ([figure 4](#)) to be compared to measured records of strain. As mentioned already, the plate elements in this level of modeling are not yet small enough to get strains equal to the measured ones, but the shape and the influence of the damping parameter on dynamics can be studied. A comparison to figure 9 reveals a lesser dynamic component in measured strains, which means that the assumed damping was still too high.

The dynamic portion of the front wheel contact forces are presented in [figure 5](#) for two different surface qualities. The difference in the dynamic increment of wheel loads is high, as expected. The influence of the elastic bridge structure on the wheel loads is not recognizable.

The upper two curves in [figure 6](#) show the influence of the bridge damping on the deflection at two points of the structure. When the simulation is calculated without damping of the bridge, strong dynamic effects can be seen; when the truck drives to the second span and when the bridge is vibrating without the truck. The lower curve presents the deflection of two points of the truck body influenced mainly by the roughness function of the surface and by dynamics and only relatively little by the deflection of the bridge.

4.2 Strain distribution and deformation of the structure

The strain distribution is dependent on the location of the truck on the bridge and on the degree of dynamic excitation. In [figure 7](#), the truck is in the middle of the first span. The upper contour plot presents the strains in the longitudinal direction for the steel box. The lower plot shows the bending strains of the concrete slab in the transverse direction; an animation of these plots in particular indicates the local behaviour in accordance with the measured strains in figure 10a.

An animation of the deflections of the bridge model reveals a relatively static behavior when the truck crosses the first span ([figure 8a](#)). Without damping in the bridge model, the dynamic response increases a lot when the truck drives to the second span and there is still strong dynamics (free vibration), including torsion, when the truck has left the bridge ([figure 8b](#)).

5 MEASUREMENTS AND TRUCK-LOAD IDENTIFICATION

Strain records were measured at Belleville bridge under traffic to receive data to calibrate the FE model and to study the characteristics of the measurement point with respect to its suitability for B-WIM (bridge-weigh-in-motion) algorithms to measure truck loads. To evaluate gross loads based on measurements, the global response, (e.g. bending at midspan without detailed influence of axles), should be measured, whereas local response, (e.g. bending of the concrete plate in transverse direction or shear strains near to the pier), could provide better information with respect to axle loads. At the bridge of concern there is a matching of frequencies of the bridge with geometric frequencies due to the axle spacing and the average speed of the trucks. The general method of separating dynamics by frequency filtering can spoil the strain record with respect to wheel load information.

In [figure 9](#) the strain records representing bending in the middle of the first span and shear near the pier are given. There is the same strong dynamic effect when the truck comes to the second span as obtained in the simulation.

The local reaction due to a crossing truck is presented in [figure 10](#) where the record of the transverse bending of the concrete plate is compared to longitudinal bending. As this record shows nearly no dynamics, it should provide optimum information for axle measurements.

6 SUMMARY

The aim of this paper was

- to describe a FE based method to perform simulations of trucks crossing bridges,
- to present and discuss numerical results based on real structures and
- to compare numerical and measured strains to look for the optimum measurement points with respect to the B-WIM algorithm.

The simulation procedure provides, as shown, valuable and detailed results for the interactive dynamic behavior of bridge and truck.

The study of different measurement points on the bridge with respect of their usefulness for the WIM method is one of our main tasks at the moment.

The experiment with the instrumented truck, planned in early 1998, can provide a lot additional information to learn how to improve the models for even better simulation results.





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AUTHOR BIOGRAPHY

The author is a senior engineer at the Technical University of Munich in the institute of structural mechanics: <http://www.baume.bauwesen.tu-muenchen.de/>

His main fields of research are: - simulation of vehicles and infrastructure interaction,

- FE modeling of structures, calibration procedures,
- dynamic measurements of structures, - signal analysis.

■ monitoring of structures with respect to fatigue and dynamic behavior.

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This research has received financial support from the Transport Directorate, DGVII, of the European Commission under the 'WAVE' project. WAVE (Weigh-in-motion of Axles and Vehicles for Europe) is a transport research project in the 4th Framework program.



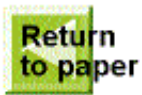
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Fig. 1: Midspan of Belleville bridge/France



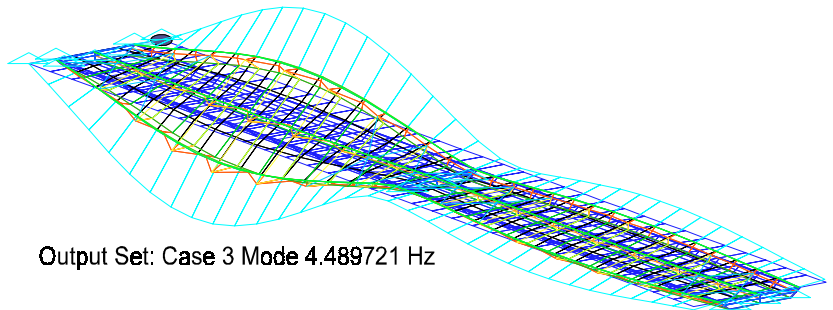
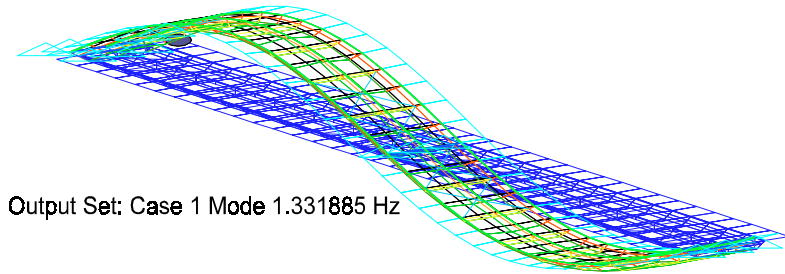


Fig. 2: Mode shapes: 1st bending and 1st torsion



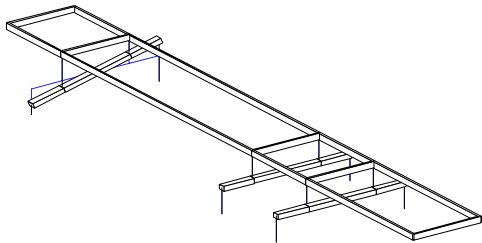
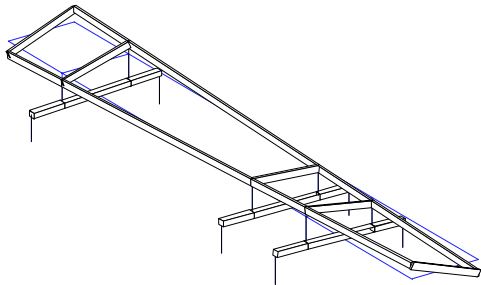
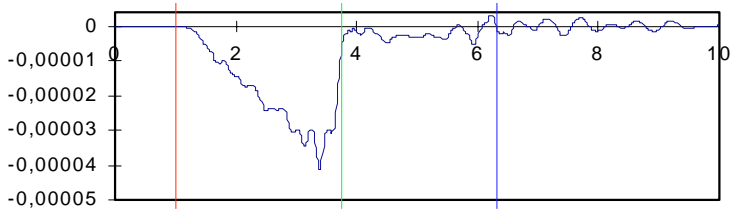


Fig. 3: Mode shapes of VTT truck model:
frame twist and front axle roll



shear strain near pier (element 3015)



bending strain, middle of 1st span (element 4040)

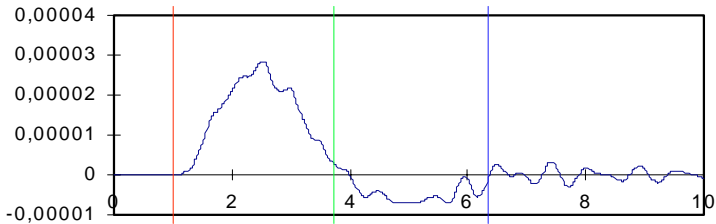
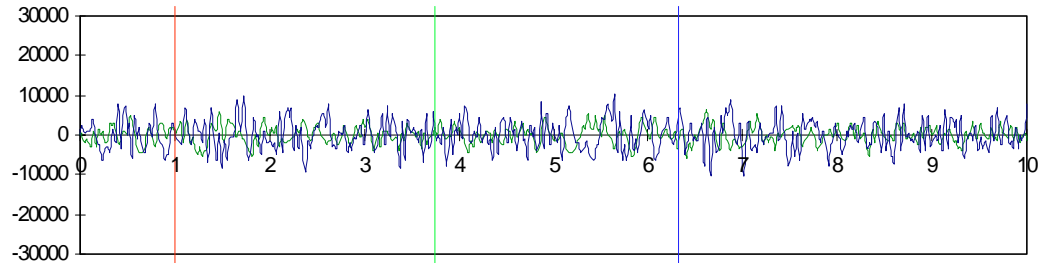


Fig. 4: Strain curves, steel box, bridge with small damping
vertical markers: 1st axle at bridge, pier, end of bridge



a) good surface quality



b) average to bad quality

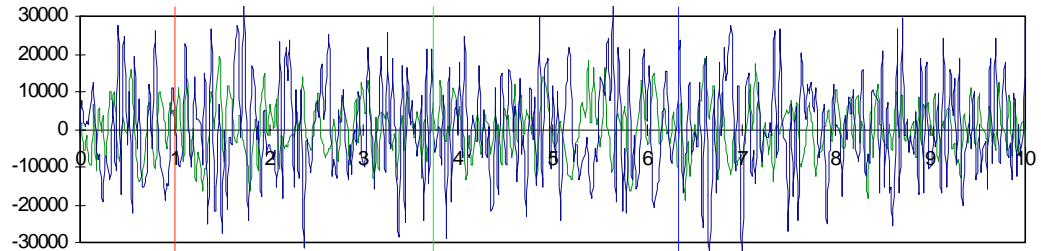


Fig. 5: Front and rear wheel forces [N] by time [s]



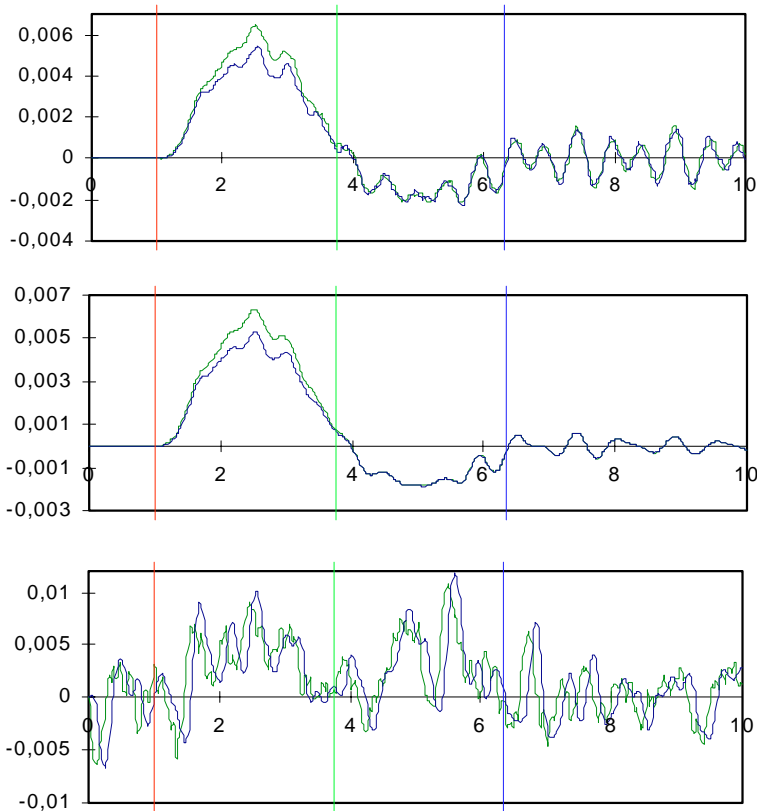


Fig. 6: Deflections [m] by time [s], good surface quality:

- a) 2 points at the bridge, no damping
- b) 2 points at the bridge, small damping
- c) 2 points of the truck body



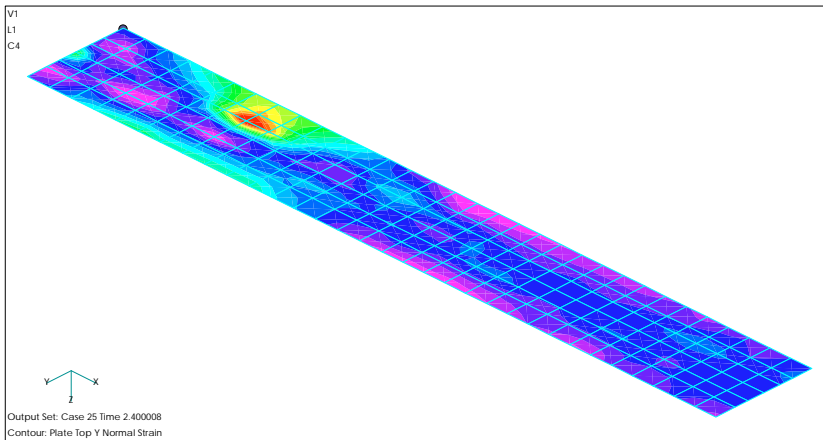
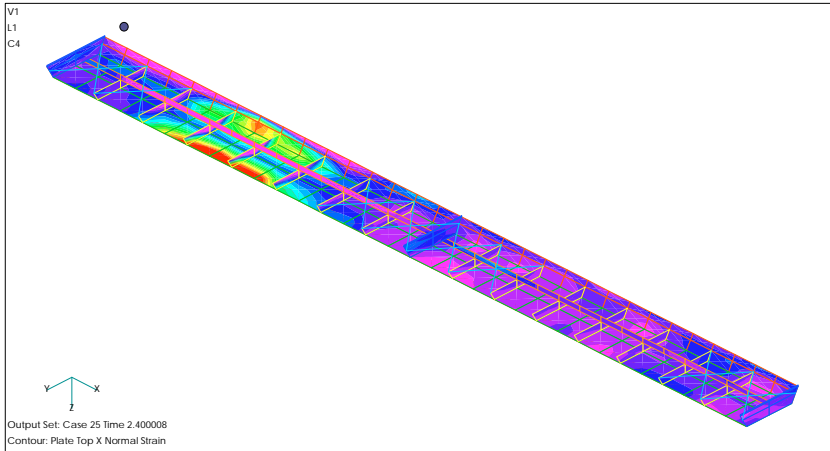
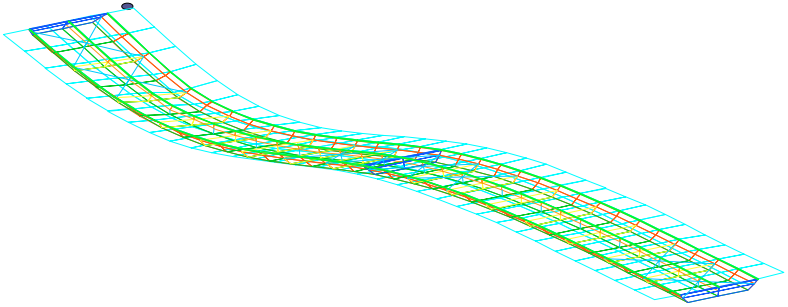


Fig. 7: Strain contour plots: a) steel box girder, ϵ in x -direction
b) concrete plate, ϵ in y -direction



V1
L1
C4



V1
L1
C4

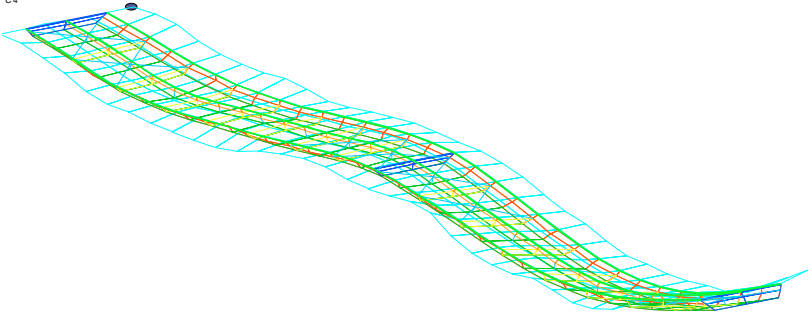


Fig. 8: Deflections (different scales): a) truck on 1st span
b) free vibration



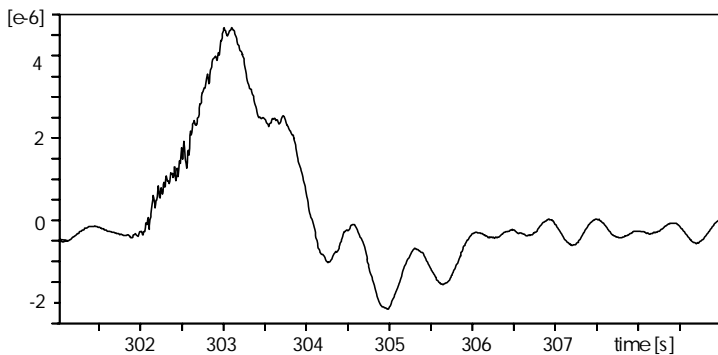
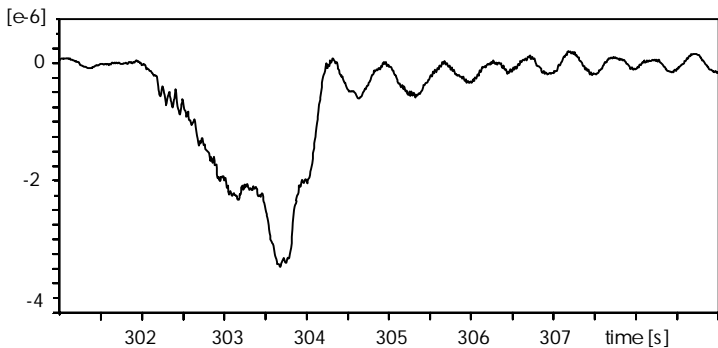


Fig. 9: Measured strains: a) steel shear b) steel bending



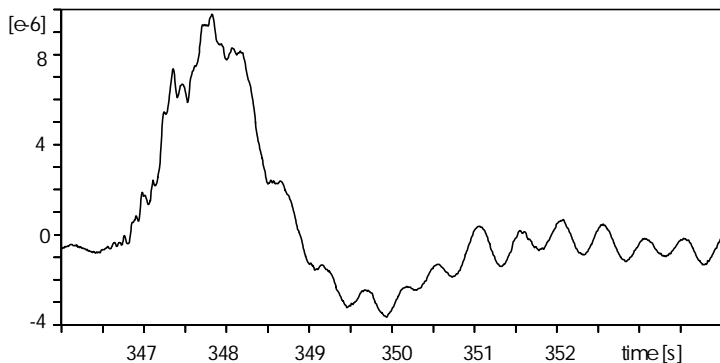
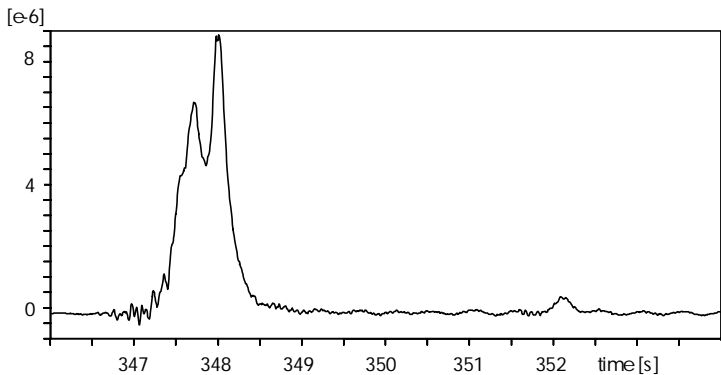


Fig. 10: Strains: a) concrete bending, transverse direction
b) steel bending, longitudinal direction

